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Bridging the Gap Between Formal and Informal Science Education: Exploring the Effects of Socio-scientific Museum Exhibitions on Students' Critical Energy Literacy

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Abstract

This dissertation is the result of the combination of three manuscripts. The first manuscript is a comprehensive account of the content and design of a modern socio-scientific exhibition on the energy transition, on which this dissertation is based and in the development of which the author of this dissertation acted as chief curator. The energy transition is an extremely urgent and complex societal undertaking away from a fossil fuel-based energy system towards a more sustainable energy system to mitigate climate change and resource scarcity. This manuscript provides curators' insights into how modern socio-scientific exhibitions on such urgent topics can be developed in a systematic and theory-driven manner, and forms the basis for linking the research findings of the subsequent studies back to this highly complex and rich learning experience. These relatively new types of exhibitions can be expected to have great potential to complement formal education in preparing students to engage with the complex socio-scientific issues that define the challenges they will face in their lifetimes. The second and third manuscripts examine the extent to which this modern socio-scientific exhibition helped students develop their critical energy literacy, a complex construct that should help students become able and willing to engage with energy-related issues in ways that support the broader goals of a global energy transition. The second manuscript focuses on how students´ cognitive-affective domain of their critical energy literacy developed after their exhibition visit while the third manuscript concentrates on the development of the behavioral domain of students´ critical energy literacy. These two manuscripts drawing on different features of the exhibition and targeting different areas of critical energy literacy, both provide evidence that the exhibition did indeed have a positive impact on students' critical energy literacy in a progressive Vision II/-III sense. In addition, the second and third manuscripts also investigate the extent to which the observed changes in students' critical energy literacy depend on students' prior conceptual knowledge about energy and their interest in the topic of the energy transition. Thus, these manuscripts bridge the gap between formal and informal education as they examine the extent to which foundational elements of energy literacy, like conceptual energy knowledge and topic interest, as they are currently addressed mostly in formal education, influence students' development of a progressive agential critical energy literacy, in a holistic socio-scientific learning environment. Both studies found that students' prior conceptual knowledge of energy, but not students' prior interest in the topic, had a positive influence on students' critical energy literacy after their exhibition visit. Additionally, the second manuscript identified a rather low level of conceptual energy knowledge as a necessary condition for the observed development of students` cognitive-affective critical energy literacy. Overall, this dissertation adds to the research base on how combining the inherent strengths of informal and formal learning sites can help students meet the challenges of the 21st century

Zusammenfassung

Diese Dissertation basiert auf drei Manuskripten. Das erste beschreibt die Konzeption einer modernen sozialwissenschaftlichen Ausstellung zum drängenden gesamtgesellschaftlichen Prozess der Energiewende und gibt Einblicke, wie solche Ausstellungen systematisch und theoriegeleitet entwickelt werden können. Es bildet die Grundlage für die Rückbindung der folgenden Forschungsergebnisse an dieses hochkomplexe und reichhaltige Lernangebot, an dessen Entstehung die Autorin dieser Dissertation als leitende Kuratorin beteiligt war. Diese relativ neue Ausstellungsform hat theoretisch großes Potenzial, formale Bildung in der Befähigung von Schüler:innen zu unterstützen, sich mit komplexen, für sie hochgradig relevanten sozio-wissenschaftlichen Herausforderungen auseinanderzusetzen. Im zweiten und dritten Manuskript wird deswegen untersucht, inwieweit die Ausstellung Schüler:innen geholfen hat, die kognitiv-affektiven und behavioralen Bereiche ihrer kritischen Energiekompetenz zu entwickeln, die sie befähigen soll, sich mit energiebezogenen Themen in einer Weise auseinanderzusetzen, die die umfassenderen Ziele einer globalen Energiewende unterstützt. Diese Manuskripte, die sich auf verschiedene Merkmale der Ausstellung stützen und auf unterschiedliche Bereiche der Energiekompetenz abzielen, liefern beide Belege dafür, dass die Ausstellung einen positiven Einfluss auf die Energiekompetenz der Schüler:innen im Sinne einer progressiven Vision II/-III *scientific literacy* hatte. Darüber hinaus wird im zweiten und dritten Manuskript untersucht, inwieweit die beobachtete Weiterentwicklung der kritischen Energiekompetenz vom konzeptuellen energiebezogenen Vorwissen der Schüler:innen und ihrem Interesse am Thema Energiewende abhängen. Durch diese Verbindung formaler und informeller Bildung lässt sich darstellen, inwieweit grundlegendere Elemente von Energiekompetenz, wie konzeptuelles Energiewissen und thematisches Interesse, wie sie derzeit vorwiegend in der formalen Bildung adressiert werden, die Entwicklung einer progressiven, handlungsorientierten Energiekompetenz der Schüler:innen in einer ganzheitlichen sozio-wissenschaftlichen Lernumgebung beeinflussen. Beide Studien deckten auf, dass das konzeptuelle Vorwissen der Schüler:innen, nicht aber ihr Vorinteresse, die Entwicklung einer kritischen Energiekompetenz durch die Ausstellung begünstigte. Im zweiten Manuskript zeigte sich zudem, dass bereits ein geringes konzeptuelles Energiewissen als notwendige Voraussetzung für die Entwicklung der kognitiv-affektiven kritischen Energiekompetenz der Schüler durch die Ausstellung ausreichte. Insgesamt leistet diese Dissertation einen Beitrag zur Forschungsbasis darüber, wie die Kombination der inhärenten Stärken informeller und formaler Lernorte Schüler:innen dabei unterstützen kann, die Herausforderungen des 21ten Jahrhunderts zu meistern.

Included Publications

This dissertation is the culmination of three manuscripts, two of which have been published in international peer-reviewed journals, and the third of which is currently being submitted for publication. The author of this dissertation is the first author of all three articles and played a leading role in their development, conceptualization, data collection, qualitative and statistical data analysis, writing and submission. She was also the chief curator of the exhibition, that forms the starting point for this dissertation project. ***Manuscript A***. is a comprehensive account of the content and design of a modern socio-scientific exhibition on the energy transition, on which this dissertation is based. This manuscript provides curators' insights into how modern socio-scientific exhibitions can be developed in a systematic and theory-driven manner, and forms the basis for linking the research findings of the subsequent studies back to this highly complex and rich learning experience. Dr. Christina Newinger contributed significantly to its design and writing. ***Manuscript B*** has been submitted for publication and focuses on promoting the cognitive-affective domain of critical energy literacy through a modern socio-scientific museum exhibition and its dependence on conceptual energy knowledge and topic interest. **Manuscript C** focuses on the behavioral domain of critical energy literacy and the identity-based approach integrated in said modern socio-scientific museum exhibition. Prof. Dr. Doris Lewalter and Prof. Dr. Jeffrey Nordine provided critical review of the study design and surveys for **Manuscripts B and C**, contributed to the development of the manuscripts, and read and approved the submitted versions. Dr. Melanie Keller discussed the statistical analyses with the first author, contributed to the development of Manuscripts B and C, and read and approved the submitted versions. Dr. Stephanie Moser developed and discussed the analysis via Necessary Condition Analysis with the first author, contributed to the development of parts of Manuscript B, and read and approved the submitted version.

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Manuscript C: Kellberg, S., Nordine, J., Keller, M., & Lewalter, D. (2023). Fostering students' willingness to act pro-environmentally through an identity-oriented socio-scientific exhibition on the energy transition. *Frontiers in Education*, 8, Article 1081633. https://doi.org/10.3389/feduc.2023.108163

Contents

1. Introduction

We live in a world of great uncertainty, facing serious environmental and socio-economic crises such as climate change, resource scarcity, pollution, or biodiversity loss (United Nations, 2021), with all their implications for the health of our planet and its inhabitants. To address these challenges, the United Nations General Assembly (United Nations, 2015) identified seventeen major global goals, called the Sustainable Development Goals (SDGs), with the aim “to secure a sustainable, peaceful, prosperous and equitable life on earth for everyone now and in the future” (Rieckmann, 2017, p. 5). These goals are not only extremely important to achieve, but also very urgent in terms of time, as scientists have repeatedly emphasized the urgency of adequately addressing and mitigating climate change and their serious concern to keep global temperature rise below 2ºC of warming (Future Earth, 2020, p. i). The extent to which (and how quickly) these goals can be achieved will largely depend on today's education (Schleicher, 2018, p. 227) and how it prepares students to “take advantage of science in the generation of adaptative, resilient, and sustainable responses to unpredictable changes of today” (Valladares, 2021, p. 582). But although various educational movements and frameworks address the need to help students become scientifically literate in ways that enables them to engage with and act on these challenges, there are continuous but competing visions of what such a scientific literacy should entail, when it comes to teaching science in school (e.g. Roberts, 2007, Valladares, 2021).

Critical energy literacy can be placed at the progressive end of this scientific literacy continuum and can be identified as an important educational goal as societies worldwide seek to mitigate climate change by implementing an energy transition away from a fossil fueled energy system towards a sustainable energy system. As there are different conceptualizations of energy literacy, this dissertation first examines which elements of critical energy literacy appear to be paramount for students to be able and willing to participate in a global energy transition, and then explores how learning opportunities should theoretically be designed to holistically promote these elements. In doing so, this dissertation extends the insights of the Socio-scientific Issue Framework (SSI), which emphasizes perspective-taking and socio-scientific reasoning (Presley et al., 2013, Sadler et al., 2016) by integrating "identity work" (Calabrese Barton et al., 2013) as a process that theoretically promotes pro-environmental behavior (Stapleton, 2015). Thus, this dissertation aims to advance the adequacy of SSI-learning environments for fostering students' critical scientific literacy toward the most progressive end of the scientific literacy continuum, which strongly includes fostering students' sense of agency. However, although science education aims to equip students with competencies to guide their learning and decision-making outside of school and to meet the existing challenges of the 21st century (Reimers & Chung, 2016), it largely emphasizes the acquisition of conceptual knowledge and mostly revolves around separate domains (OECD, 2019), placing current formal education mostly at the more conservative end of the scientific literacy continuum (Osborne, 2007; Hodson, 2020).

Recently, parallel perceptions and movements in the museum sector have culminated in so-called "critical" or "agential" exhibitions (Pedretti & Navas Iannini, 2020a), which aim to provide visitors with critical insight into controversial or socio-scientific issues and increasingly tend to address visitors as the agents of change they might become (Navas Iannini & Pedretti, 2022, p. 60). Since these types of exhibitions tend to overlap and both reflect, albeit to different degrees, what the SSI-movement has been advocating for the past several decades (Zeidler et al., 2019) this dissertation refers to them as modern socio-scientific exhibitions (modern SSI-exhibitions). In addition, these exhibitions provide visitors with great opportunities for identity work (Rounds, 2006) due to the free-choice learning that takes place in them and should therefore have an overall positive effect on students' critical scientific literacy. For these promising learning environments to reach their full potential, however, they must be conceived and designed in a theory-driven manner. The first manuscript on which this dissertation is based illustrates what such a purposeful design might look like. In order to test this hypothesized potential, this dissertation project then examines the extent to which such a modern SSI-exhibition on the energy transition has a positive effect on students' critical energy.

Because free-choice learning in any exhibition is highly dependent on visitors' prior knowledge and interests (Falk & Storcksdieck, 2005; Falk et al., 2011), this dissertation also examines the extent to which students' prior conceptual knowledge of energy and interest in the topic of the energy transition influence changes in students' critical energy literacy through a visit to a modern SSI-exhibition on the energy transition. By including both students' prior conceptual knowledge of energy and their interest in the topic of the energy transition as independent variables, this dissertation attempts to 1) bridge the gap between formal and informal education and also 2) examine the extent to which more foundational elements of energy literacy like conceptual energy knowledge and topic interest, as they are currently mostly addressed in formal education, influence students' development of a progressive critical energy literacy that includes critical evaluation and agency. In doing so, this dissertation project aims to add to the research base on the extent to which school-based knowledge and interests help students navigate complex SSI-learning environments, and how combining the inherent strengths of informal and formal learning sites can help students meet the challenges of the 21st century.

2. Preparing Students for 21st Century Challenges

This section shows how science education is continually asking what scientific literacy, the overarching goal of science education, must encompass. Upon this question and its answer hinges what science education focuses on when equipping students with what they need to know and be able to do to meet the 21st century challenges they will inevitably face in their lives. With and around these progressing visions of scientific literacy, various educational movements have developed in order to integrate these visions into science teaching and learning.

2.1 The Continuum of Scientific Literacy

The overarching goal of science education is to help students to become scientific literate; however, scientific literacy is a theoretical construct that has been and continues to be widely interpreted and defined (Hodson, 2003; Roberts, 2007; Valladares, 2021). These interpretations have influenced approaches to science education, from a focus on the transmission of scientific concepts to stressing the impact of science and technology on society and, more recently, to "the role of science as a tool for social change" (Valladares, 2021, p. 558).

A comprehensive review of the different interpretations of scientific literacy led Roberts (2007) to use the term as “a way of framing outcomes for science education” (Romine et al., 2017, p. 275) into two main visions of scientific literacy. These outcomes were either defined by the science disciplines themselves, meaning that science education should help students develop a better understanding of the scientific concepts and competencies important to those disciplines. Roberts called this the “Vision I” of scientific literacy (Roberts, 2007). Here, students are envisioned to become interested and competent in science and technology, with the primary goal of leading them to careers in the STEM sector. However, this vision has also been criticized for perpetuating a technocratic and economic mindset too inflexible and at risk of becoming outdated when students actually enter a rapidly changing world of work (Smith & Watson, 2018).

In the second major vision of scientific literacy (Vision II) students are to engage with scientific ideas and practices in meaningful societal contexts that are either related to or influenced by science in order to help them understand the usefulness of scientific knowledge in everyone's lives. These two visions form a continuum from the "cannon of orthodox science" (Roberts, 2007, p. 730) i.e. Vision I scientific literacy, which provides students with scientific facts and concepts, to the provision of learning opportunities revolving around every day and contextualized scientific and technological issues, i.e. Vision II scientific literacy, which leads to "a broad and critical understanding of the nature of science and its socio-political contexts and aspects of citizenship" (Pedretti & Navas Iannini, 2020a, pp. 15-16).

It has been advocated to extend this continuum even further to meet the demands of sustainable citizenship and active engagement in the challenges of the 21st century, where "[…] active participation and dialogue among all citizens on complex issues are needed […]" (Liu, 2013, p. 27). This third vision of scientific literacy (Vision III) involves greater social engagement and civic impact - aiming at socio-political action (Sjöström & Eilks, 2018) and emphasizing "knowing-in-action" (Aikenhead, 2006). Ultimately, this Vision III scientific literacy corresponds to what Hodson (2003; 2009) called critical scientific literacy, which aims at "the clarification of problems and negotiation of possible solutions through open, critical dialogue and active participation in democratic mechanisms for effecting change" (Hudson 2003, pp. 653-654).

In summary, the role of students (in education and in the world) is perceived very differently in these three versions: students in Vision I develop their skills to prepare for science careers and are thus "pure science learners" (Liu, 2013, p. 29). In Vision II they engage with science to solve technological and societal problems but remain "science advocates" (Liu, 2013, p. 29). Finally, in Vision III they are "honest brokers" (Liu, 2013, p. 29) seeking the best possible solutions to complex social, cultural, political, and environmental problems (Valladares, 2021, p. 566).

2.2 The Necessity for Science in Context

Each vision of scientific literacy inspires different educational movements, curricular proposals, didactic strategies, and pedagogical approaches, as well as teacher training and student assessment (Roberts & Bybee, 2014), which to some extent coexist in formal and informal education (Pedretti & Navas Iannini, 2020a). At the same time, as visions, practice, and research constantly influence each other, the resulting movements themselves feed back into the ongoing discussion of educational goals and strategies. In a simplified way, one could speak of a development of science education along the continuum of scientific literacy, from traditional disciplinary and subject-specific education to the connection between science and society (i.e. STS, Science, Technology and Society) and interdisciplinary science subjects (STEM, Science, Technology, Engineering and Mathematics), to the incorporation of the multidisciplinary field of Education for Sustainable Development (EfS, ESD, ESDG) (Gamage et al., 2022) in order to promote scientific literacy in the most progressive sense. In other words, "the STEM disciplines are called upon to participate in the social process of searching, learning, and shaping with the aim of solving global sustainability issues and to critically reflect on their contribution to (non-) sustainable developments (Pahnke et al., 2019, p. 4).

Promising educational structures for this are provided by the so-called Science-in-Context (SinC) field including Science, Technology, Society, and Environment (STSE), SaQ Socially Acute Questions (SAQ) and the Socio-scientific Issue Framework (SSI) (Bencze et al., 2020). With SSI *integrating* an understanding of science content in the context of real-world socio-scientific issues and providing a clear theoretical framework (Zeidler et al., 2005; 2017) and a defined model for teaching and learning (Presley et al., 2013; Sadler et al., 2016) to help students become responsible “global citizens” (Kahn & Zeidler, 2017, pp. 261).

However, despite these goals and trends, Hodson noted just a few years ago that "our current educational priorities are [still] hopelessly misplaced, [and] inadequate to the task of preparing students for responsible and active citizenship" (Hodson, 2020, p. 597), with ever too much emphasis placed on detailed learning outcomes, teacher-centered pedagogy, and testing for "so-called standards" (ibid.). With regard to contemporary curricula and practices in science education for the 21st century, Osborne also argues that current science education is (still) focused on educating future scientists rather than future citizens (Osborne, 2007), and Bencze et al. (2020) note that despite the existence of more holistic science education movements (e.g., SinC), trends in STEM education that strongly prioritize teaching and learning in a V-I scientific literacy sense are regaining momentum in educational frameworks and are significantly compromising students' education in a Vision II/-III SL sense (Bencze et al., 2020, p. 847). In the face of such "threats" (Bencze et al., 2020, p. 847), the implementation of Vision II/-III scientific literacy in students' educational environments needs further research and support. The present dissertation therefore focuses on one particular critical scientific literacy, namely that of energy literacy, and how it can be supported through a combination of formal and informal learning environments.

3. Energy Literacy

Examples of scientific literacies at the progressive end of the literacy continuum are environmental literacy itself (e.g. McBride et al., 2013) climate literacy (e.g. Choi et al., 2021), and energy literacy (see Section 3.2). These literacies have included a behavioral dimension and the goal of motivating students to act sustainably from the earliest conceptualizations of environmental literacy in the 1990s (Chen et al., 2015, p. 202) and have always been the subject of science education and environmental education. Their inherent strong action component is more important today than ever as societies are globally trying to mitigate climate change by implementing an energy transition away from fossil fuels to sustainable energy sources.

3.1 The Energy Transition

A global energy transition is urgently needed to address climate change and increasing resource scarcity, two of the greatest challenges of the 21st century (United Nations 2021; World Economic Forum, 2021). The goal of this energy transition is to move away from fossil fuels toward low-carbon energy sources, greater energy efficiency, and energy conservation. Thereby, the transition inherently needs to address economic, environmental, and social equity

(Burke & Stephens, 2017; Miller et al. 2013) to create an overall sustainable energy system. However, such a transition involves complex, lengthy, and far-reaching political, economic, scientific, and societal changes and requires the active participation of a wide range of actors (International Renewable Energy Agency, 2021; Miller et al., 2013; United Nations Environment Programme, 2019). Therefore, the energy transition can be identified as a socio-scientific issue (SSI) that involves "social dilemmas with conceptual or technological links to science" (Sadler, 2004, p. 513), where different perspectives must be considered and where "conclusions and courses of action are underdetermined by scientific evidence" (Sadler et al., 2016, p. 75). This not only qualifies the energy transition as a socio-scientific issue, it also means that the energy transition must be understood as an open process that needs to be shaped by actors from all sectors of society (Steg et al., 2016), weighing the pros and cons of different solutions in different contexts.

Considering that these actors are not only representatives of industry and science, politics and interest groups, but also people with personal values and attitudes towards the issue, it becomes clear that a global energy transition ultimately depends on the ability and willingness of each individual to engage with the energy transition and to act in ways that promote its goals (McCaffrey et al., 2012; Sanz-Hernández, 2020). Educating students to become energy literate citizens who are 1) able to engage with this pressing socio-scientific issue, 2) able to make informed energy-related decisions, and 3) willing to ultimately act in energy-conscious ways (e.g., Lowan-Trudeau & Fowler, 2021; U.S. Department of Energy, 2017) is therefore essential. This role of education in helping students become "productive citizens in national energy policy debates and actions" (Liu & Park, 2014, p. 182) is reflected in the emphasis many education standards place on the importance of energy and energy literacy (e.g., Kultusministerkonferenz, 2005; NGSS Lead States, 2013), as well as various studies and recently published reviews on the topic (Gladwin & Ellis, 2023; Martin et al., 2020).

3.2 Defining Energy Literacy

Energy with its dependencies and impacts, is at the heart of many 21st century challenges. Therefore, the energy transition spans no less than five Sustainable Development Goals (namely SDG 7 *Affordable and Clean Energy*, SDG 9 *Industry, Innovation and Infrastructure*, SDG 11 *Sustainable Cities and Communities*, SDG 12 *Responsible Consumption and Production,* and SDG 13 *Climate Action*; for more information see Rieckmann, 2017). Yet despite its centrality and the fact that energy literacy has indeed received increasing attention in the last decades, an ultimate definition remains elusive (Gladwin & Ellis, 2023).

The best-known work on energy literacy was done by DeWaters and Powers, whose description and instruments (DeWaters et al., 2013; DeWaters & Powers, 2009, 2011, 2012) have been used worldwide for studies regarding the energy literacy of middle school students (Akitsu et al., 2017; Lee et al., 2015; Lee et al., 2022). The two authors describe an energy literate person as someone with a basic understanding of the concept of energy, that has ideas about the impact that energy production and consumption have on the environment, and that ultimately arrives at energy saving behavior through critical thinking and evaluation. The U.S. Department of Energy outlines energy literacy as "an understanding of the nature and role of energy in the universe and in our daily life" (U.S. Department of Energy, 2017, p. 1), as well as the ability to apply that understanding to answer questions and solve problems but also stresses very concrete knowledge and skills when it describes an energy literate person as someone who knows (accurately) "how much energy" they use and how to "trace energy flows" (U.S. Department of Energy, 2017, p. 1). In addition, a group of scholars stresses the relationship between energy literacy and financial literacy (Blasch et al. 2018; Brounen et al., 2013; Kalmi et al. 2017, 2021). Although the idea of linking energy literacy to other, perhaps more basic literacies, is comprehensible, but the focus on personal financial budgeting decisions takes a primarily economic perspective that leaves the socio-political dimension of the energy transition in the background.

Pushing the definition of energy literacy towards the Vision II/-III scientific literacy end, Chen, Liu, and Chen (2015) explicitly add a "civic responsibility" to participate in energy conservation activities for a sustainable society to the catalog of an energy literate person. Their conceptualization includes knowledge of energy concepts, the ability to decide how to use energy and evaluate "energy-related issues" as well as information about them, and a low-carbon lifestyle (Chen et al., 2015, pp. 205-206). In addition to the individual use of (electrical) energy, the study examines the aforementioned lifestyle in terms of individual consumer choices and attitudes which besides the individual use of (electrical) energy investigates the behavioral dimension of energy literacy in regard to individual consumer decisions and attitudes. However, much of the research on conceptualizing or measuring energy literacy remains in the realm of households and individual responsibility for energy consumption (Adams et al., 2022). In terms of the systemic scope of the energy transition, though, it is important to note that a genuine transition does not emerge solely as a passive result of reduced (energy) consumption, but rather through 'the driving force of multiple actors purposefully shaping transitions around a shared long-term vision for the future' (Farla et al., 2012, p. 992).

A description that encompasses this systemic view of energy literacy in terms of a holistic energy transition comes from Lowan-Trudeau and Fowler (2021). In their theoretical paper, the authors define *critical* energy literacy, as a wide "understanding of the social, environmental, political and economic challenges, benefits and impacts of various energy sources, transportation technologies and construction technologies including, but not limited to wind, solar, passive, small- or largescale hydro, tidal, geothermal, oil and gas, coal and nuclear" (Lowan-Trudeau & Fowler, 2021, p. 3). This understanding enables energy literate citizens to comprehend the systemic scope of the energy transition and to evaluate the pros and cons of different energy sources and their implementation as a basis for their decisions regarding their individual or collective actions toward energy transition goals.

3.3 Domains of Energy Literacy

Based on de Waters and Powers Work (2009) most of the energy literacy- conceptualizations span three domains: The cognitive domain including content knowledge and cognitive skills, the affective domain containing positive attitudes towards energy conservation or the sustainable use of energy sources as well as respective values and the behavioral domain including predispositions to behave and actual behavior (DeWaters et al., 2013, p. 57). This tripartite division of domains is also reflected in the learning objectives of the SDGs. Here, the cognitive domain consists of the knowledge and thinking skills needed to better understand the various goals and the challenges of achieving them. The affective (= socio-emotional) domain consists of students´ inclination and skills that enable students to collaborate, negotiate, and promote the SDGs, as well as self-reflection, values, attitudes, and motivation, and the behavioral domain describes action competencies (Rieckmann, 2017, p. 10).

While it is often assumed that energy-related knowledge forms the cognitive basis of energy literacy, and that affective elements such as attitudes build on it, and both positively influence the behavioral domain of the energy literate person, research has not yet been able to empirically support this assumption (Białynicki-Birula et al., 2022). Instead, promoting critical energy literacy for greater socio-cultural engagement in the energy transition requires a confluence of cognitive, affective, and behavioral educational approaches.

4. Promotion of Critical Energy Literacy

A number of pedagogical movements in the Science-in-Context field (see Section 2.2) advocate for the advancement of a progressive critical scientific literacy. This array includes the Socio-scientific Issue Framework (SSI), which provides practitioners and researchers with a comprehensive framework (Zeidler et al., 2005, 2017) and a defined teaching and learning model (Presley et al., 2013; Sadler et al., 2016) to help them support students in becoming responsible "global citizens" (Kahn & Zeidler, 2017, p. 261). Besides teaching content knowledge, attitudes, and skills related to a particular socio-scientific issue (e.g., the energy transition), SSI also focuses on providing practice in and measuring transferable skills such as socio-scientific reasoning (Romine, et al., 2017; Sadler, 2009, p. 701) in its educational and teaching approaches (Presley et al., 2013, Sadler et al., 2016). However, SSI teaching approaches - at least so far - only indirectly addresses the development of pro-environmental behavior and agency through socio-scientific reasoning (Bencze et al., 2020, p. 837; Bossér, 2018, p. 24). That is, there is an assumption that by gaining insight into the ethical dilemma, as well as the various resolutions and viewpoints that come with any socio-scientific issue, students can develop “*dispositions* toward environmental stewardship and conservation” (Kinslow et al., 2018, p. 19). In order to strengthen this dispositional development, it is useful to pay attention to another process in addition to socio-scientific reasoning that can be incorporated into SSI-learning environments for students to engage with. The process considered in this dissertation refers to "identity work" (Calabrese Barton et al., 2013), which theoretically fosters students' social-environmental identities (Stapleton, 2015) and thus their behavioral tendency toward environmentally friendly behaviors (in the context of promoting the energy transition). With the integration of identity work this dissertation aims to push the suitability of SSI-learning environments and how well they foster scientific literacy towards the Vision II and Vision III end of the continuum (Manuscript C).

4.1. Fostering the Cognitive-Affective Domain

SSI-learning experiences should be designed to “help students become better at dealing with complex issues like SSI” (Zeidler et al., 2019, p.1) and to prepare them to “engage in decision making and position taking” (ibid.) – for example in the context of the energy transition. Concretely in relation to environmental literacy it has been shown that the accordingly thematically situated SSI approach increased the “cognitive and affective portions of the curriculum” (Kinslow et al., 2018, p. 1) resulting in students awareness gain and increased competency “for analyzing environmental issues, and evaluating impacts and solutions” (ibid.).

4.1.1 Socio-scientific Reasoning and Perspective Taking

In order to provide students with a Vision II scientific literacy, the implementation of SSI into science education, aims at encouraging students to take part in debates and decision making regarding complex socio-scientific issues. For this, students have to be supported in developing their scientific knowledge, critical thinking skills, and understanding of the complexities of SSI and “need to be encouraged to develop a sense that their viewpoints on the issues matter” (Bossér, 2018, p.82). When it comes to designing learning environments, this implies that these need to give students the opportunity to explore various perspectives onto the regarding socio-scientific issue as well as the chance to practice the above-mentioned critical thinking skills.

Socio-scientific reasoning and perspective taking have been identified as two of the key critical thinking skills that need to be realized in SSI-learning environments in order to have a significant pedagogical impact on students' critical scientific literacy, as the development of these intellectual skills affects "virtually any of the central problems situated in environmental or eco-justice education" (Zeidler & Newton, 2017 p.57). Socio-scientific reasoning is in itself a construct that “describes thinking practices that individuals use as they make sense of, consider solutions for, and work to resolve complex SSI” (Romine et al., 2017, pp. 276–277) and that is expected to improve when students are given the opportunity to participate in appropriate learning environments. Although socio-scientific reasoning was originally “conceptualized as a means of understanding how individuals negotiate different aspects of complex, social issues” (Sadler, 2009, p. 700), it can also be incorporated into instruction (ibid.), i.e., in the classroom or informal learning environments, by having students evaluate the trade-offs of competing viewpoints regarding different solutions to socio-scientific challenges. Perspective taking is the ability “to recognize and consider the diverse cognitive and emotional viewpoints of others within SSI” (Kahn & Zeidler, 2017, p. 263) and is described as a “keystone (Zeidler, et al., 2019, p. 4) for supporting socio-scientific reasoning. Here, it is important to keep in mind that students do not necessarily know how to evaluate pure information about different viewpoints on different aspects of socio-scientific issues, and therefore need support in identifying where these different perspectives *come from* so that students can then evaluate them in relation to their own position and attitude on the particular socio-scientific aspect (Kahn & Zeidler, 2017).

In order for perspective taking and socio-scientific reasoning to work together to mediate solution finding and decision making regarding, for example, the energy transition, students need opportunities to examine each SSI topic, i.e., the energy transition, "from the perspectives of multiple stakeholders" (Zeidler & Newton, 2020 p.57) and action options (Jorgenson et al., 2019). In addition, SSI-learning environments need to be designed to help students recognize the inherent complexity of socio-scientific issues and the need for ongoing inquiry, as well as to help them develop a healthy scepticism when confronted with potentially biased information about these topics (Sadler et al., 2007, p. 374). Moreover, students benefit most from these learning environments when they facilitate independent learning (Wang & Wang, 2023). Or, as Knipfler summarizes, when confronted with arguments from multiple perspectives, people have to rely on their own reasoning about the advantages and disadvantages of various alternative solutions (Knipfler, 2009, p. 37).

Therefore, SSI-learning environments should be designed to provide opportunities for students to engage in reasoning, argumentation, and decision-making practices in structured activities. By engaging in these practices, students are empowered to identify their own position on a socio-scientific issue through exposure to multiple perspectives (Presley et al., 2013), including the environmental or socioeconomic aspects of, for example, climate change and the "policies designed to address the issue" (Presley et al., 2013, p. 29). It is also recommended to include a "culminating experience where learners can synthesize ideas" (Herman et al., 2017, p. 146) and that allows learners to "integrate what they have learned with their prior knowledge" (Presley et al., 2013, p. 28), i.e. in the form of a debate or role play (ibid.).

4.2 Fostering the Behavioral Domain

There exists a vast body of interventions studies, targeting energy related behavior in order to mitigate climate change and resource scarceness and several review articles comparing these studies classifying them for example by intervention tools (Delmas, 2013), the technologies that are associated with energy usage (Nisa, et al., 2019) or the targeted area of energy reduction (Composto & Weber, 2022). But a recurring problem with promoting behaviors that could accelerate the energy transition is that most studies attempting to promote such behaviors are limited to a single energy sector (Rau et al., 2022) or focus exclusively on the realm of individual energy consumption (e.g., Abrahamse & Steg, 2013; Coskun et al., 2015). Moreover, these limitations present an overly “simplistic and individual approach to environmental problems and their causes" (Jensen & Schnack, 1997, p. 172) and frankly ignore that "large institutions such as government and industry are major contributors to waste, pollution, and the consumption of nonrenewable resources, as well as structural barriers to greener lifestyles" (Chawla & Cushing, 2007, p. 438). In short, environmentally friendly behavior limited to the private or individual sphere is simply not sufficient to "stop global warming" (McGuire, 2015, p. 696). A successful intervention to build critical energy literacy therefore needs to communicate that a successful energy transition requires a wide range of measures (Steg et al., 2021, p. 3) including direct and indirect, individual and collective behavior in the areas of consumption, housing, mobility, food, energy production, and transportation, as well as participation in energy policy discourse (Brosch et al., 2016, p. 2; Michel, 2018).

4.2.1 Agency, Values, and Attitude

But while providing information about all of these interrelated issues might be an important first step towards the development of critical energy literacy, research shows that factual knowledge alone is not sufficient to promote pro-environmental behavior (Allen & Crowley 2017, p. 300; Sutton & Robinson 2020, p. 3). Rather, it is necessary to give students a sense of agency and relevance (Braus, 2013, p. 29), provide them with "action knowledge" (van de Wetering et al., 2022, p. 9), and give them opportunities to directly engage in such behavior (Chawla & Cushing, 2007, p. 441, Chen & Liu, 2020, p. 10). However, as Jensen and Schnack note in their seminal work on agency, this is only true as long as students are not overwhelmed by "how bad things really are" (Jensen & Schnack, 1997, pp. 171-172), feel helpless, or feel “like their individual actions might have no significant impact” (Kollmuss & Agyeman, 2002, p. 255). These are crucial aspects for the design of critical energy or scientific literacy-interventions.

Additionally, to actually engage in such actions, their impact must also be consistent with people’s personal values and attitudes. However, studies show that there seems to be only a "modest relationship" (Stets & Biga, 2003, p. 398) between environmental attitudes and behavior, and that attitudes generally predict behavior only under certain conditions (McGuire, 2015, p. 699) and with (very) small effects (Kollmuss & Agyeman, 2002, p. 252). In contrast, values are more behaviorally controlling (e.g., Bolderdijk et al., 2013), and values reflecting concern for nature and the environment have been shown to predict sustainable energy behavior and support for sustainable energy policies (Steg, 2016). But as these values are shaped by a person's closest social group and personal cultural context (e.g., Boer & Boehnke, 2016), they are difficult to achieve through educational interventions.

4.2.2 Identity Work

The perception of measures to accelerate the energy transition or the willingness to act on them not only reflects knowledge, attitudes, and values, but also depends on factors such as group membership (Bolderdijk et al., 2013), personal needs, and everyday challenges (Steg, 2022). Thus, the willingness to engage in pro-environmental behavior ultimately depends on the whole person in their living environment. However, although it has long been known that the self and one's identity do drive behavior (Burke & Reitzes, 1981), this perspective has surprisingly rarely been incorporated into the design of educational interventions

A person's identity refers to the many traits; attitudes; cognitive structures; and. the many roles and relationships that each person holds (Guenther et al., 2020). Together, they form a person's self-concept, without each aspect being equally important or occurring simultaneously. Stapleton describes this when she writes: “Environmental identity could be envisioned as a section within an individual’s identity binder. The section could be thick and/or toward the front of the binder, it could be an appendix, or it could be missing altogether" (Stapleton, 2015, p. 101). Thus, the extent to which an environmental identity influences a person's behavior depends, on the one hand, on how much of the person's overall identity it represents, or how "strong" it is (Clayton, 2003). This environmental identity can be made "salient" by situationally activating it in a person's consciousness (Rahmani et al., 2022, p. 2), thus bringing it to the forefront of a person's "identity binder". Evidence suggests that identity salience may even be a stronger predictor of behavior than identity strength (Rahmani et al., 2022) and may be fostered by sociocultural interactions (Verhoeven et al., 2019, pp. 52-53).

In this context, Kempton and Holland (2003) describe a “social environmental identity” by which people define their position in relation to others in terms of their environmental attitudes and lifestyles, and describe its development in three stages: awareness or consciousness of environmental issues, identification with and self-understanding as an actor in the environmental context, and increased knowledge of how to engage in environmental practices (Kempton & Holland, 2003, as cited in Stapleton 2015, p. 96). This environmental identity is constantly updated and recreated through social interactions and is largely influenced by education and training (Stapleton 2015, p. 97). Therefore, repeated opportunities for “identity work” (Calabrese Barton et al., 2013) in learning environments that provide students with opportunities for “participation and action in environmental activities as well as recognition as an environmental actor have the potential to further environmental identity development” (Stapleton, 2015, p. 107) which in turn can lead to improved environmental behaviors.

Concretely and for critical energy literacy, environments that allow students to engage in “the action of gathering information, questioning, experimentation, and critical reflection on one’s identifications, beliefs, qualities, and roles” (Marcia, 1966 as cited by Kaplan & Flum, 2010, p.56), should be able to promote the behavioral domain of energy literacy.

4.3 Barriers to Promoting Critical Energy Literacy in Schools

As demonstrated above, there is a growing desire for a stronger focus on societal issues in science education (Lee & Grapin, 2022) and teaching energy in context (Chen et al., 2014). Indeed, the described SSI approaches are promising and, in some cases, demonstrably beneficial (Zeidler et al., 2019) for developing critical scientific literacies, such as critical energy literacy, in students. However, implementation of SSI approaches in formal education is still proving challenging (Bossér, 2018).

There are many reasons for this, ranging from structural barriers in a school system where an interdisciplinary, cross-curricular approach is difficult to achieve (Chowdhury et al., 2020, p. 206) and where there are different priorities for teaching scientific literacy (see also Section 2.1). In addition to an overloaded and exam-oriented curriculum, the lack of systematic support, resources and tools to assist teachers and curriculum designers (Sadler et al., 2016, p. 76), as well as unclear learning objectives and underdeveloped epistemologies, are cited as major challenges in implementing SSI activities (Kilinc et al., 2017).

Finally, SSI teaching and learning require considerable time (Sadler et al., 2007) as well as "multidisciplinary expertise" (Liu & Park, 2014, pp. 181-182), yet classroom time is scarce and many teachers are only trained in specific areas of SSI topics such as the energy transition (Lowan-Trudeau & Fowler, 2021, pp. 3 & 6). In this light, out-of-school interventions may provide novel entry points by enabling socio-culturally situated learning and thus fostering critical scientific literacy development and identity work that complement school.

5. The New Role of Museums

Museum exhibitions may be particularly well suited to provide socio-culturally situated environments for students to engage with and complement formal education in helping students gain critical scientific literacy. Not only are museum exhibitions already known to play a key role in fundamentally supporting education across society (Falk & Dierking, 2010) and promoting knowledge, interest, motivation, and attitudes (Falk & Dierking, 2010; Lewalter et al., 2021; Phelan et al., 2017; Schwan et al., 2014). Museums, especially science and technology museums, are also not constrained by the "disciplinary boundaries that characterize school subjects" (Evans & Achiam, 2021, p. 9) and are able to approach science in a multidisciplinary and thematic way, facilitating social interaction and learning (Stocklmayer, et. al. 2010) and "powerful opportunities for identity work" (Rounds, 2006, p. 133). Additionally, there is an increasing willingness of museums to engage with socio-scientific issues in critical and activating ways (Pedretti & Navas Iannini, 2020a), providing schools with a growing new source of holistic educational environments.

5.1 Museums and Sustainable Development

Traditionally, museums have focused on housing and displaying collections, providing learning- and hands-on experiences (Bell, 2008), and designing environments for educational engagement in a broad sense (Pedretti & Navas Iannini, 2020a, p. 41). In recent times, however, museums have increasingly recognized their responsibility to prepare their visitors for a more sustainable future (McGhie, 2018, 2020, Sutton et al. 2017, Sutton 2020; Sutton & Robinson, 2020) and have become important sites for fostering critical scientific literacy (Hine & Medvecky, 2015; Rennie & Williams, 2006). This shift in museums` aspirations from "displaying exhibits, illustrating scientific concepts and celebrating scientific progress" (Henriksen & Frøyland, 2000, p. 394) to becoming "arenas for public debate [...] that contribute to solving global challenges" (Pedretti & Navas Iannini, 2020a, p. 23) had already emerged as a "powerful paradigm shift" (Koster, 1999, p. 287) at the end of the last century. However, it took another two decades for this movement to find its way into more or less defining and binding official museum statements.

At the second Science Centre World Summit (SCWS), science centers and science museums established the *Tokyo Protocol* as an official statement in which they declared the importance of supporting the UN Sustainability Goals with, through and for their visitors by promoting scientific literacy and participatory citizenship (SCWS, 2017). Two years later, this idea was endorsed and elevated by the International Council of Museums (ICOM) in Kyoto, resulting in the resolution "*On sustainability and the implementation of Agenda 2030, Transforming our World"* (ICOM, 2019). This resolution recognized the importance of the SDGs and the role museums have to play in shaping and creating a sustainable future as well as providing practical guidance and suggestions. Finally, in 2022 these declarations found their way into the new ICOM museum definition which inter alia states: "[…] Open to the public, accessible and inclusive, museums <u>foster diversity and sustainability</u>. […]." (The Extraordinary General Assembly of ICOM, 2022, August 24).

Pedretti and Navas Iannini described museums that followed this definition even before they officially existed as "fourth-generation science museums" (Pedretti & Navas Iannini, 2020a) that invite their visitors to "civic participation, reflexivity and engagement, and (...) work towards agency and ultimately social change" (Pedretti & Navas Iannini, 2020a, p. 63). After initially manifesting themselves primarily in communication programs such as public debates, science cafés, or educational exhibition programs, these goals, and the progressive notions of critical scientific literacy that accompany them, recently found their way into perhaps the most precious museum format: the museum exhibition.

5.2 Modern SSI-Exhibitions

Arguably the most powerful tool museums possess to tackle socio-scientific issues in order to work towards a sustainable future are exhibitions that invite visitors to engage with these topics, and help them to find their own agency and make informed responsible decisions. Pedretti and Navas Iannini label this relatively novel kind of exhibitions “critical” or “agential exhibitions”. (Pedretti & Navas Iannini, 2020a, p. 61).

As their name suggests *critical exhibitions* encourage visitors to think critically about potentially controversial science and technology issues in their socio-cultural context. They approach socio-scientific issues from a variety of perspectives and invite visitors to active participation within the exhibition (Pedretti, 2002, p. 9). The design of this exhibition type is often “emotionally charged” (Pedretti & Navas Iannini, 2020a, p. 58), stimulates visitors to question their own position (Pedretti, 2004), and emphasis dialogue and the understanding of complexities (Pedretti & Navas Iannini, 2020a, p. 70). Therefore, from an educational perspective this aligns nicely with practical scientific literacy goals in the Vision II-sense and the before discussed SSI-approach. Almost simultaneously with the continuum from science education to Vision III, which emphasizes the goal of (environmental and political) agency, Pedretti and Navas Iannini (2020) identified a new type of exhibition that explicitly pursues the same goals of “responsible citizenship, informed decision-making, action and activism” (Navas Iannini & Pedretti, 2022, p. 60). Agential exhibitions are, like critical exhibitions, situated at the intersection of Science, Technology, Society and Environment (ibid, p. 5) but additionally view their visitors as “political agents of change and transformation” (ibid.) and encourage visitors to act on a personal or societal level. This exhibition type often includes interactive and sometimes immersive exhibition designs including storytelling, opportunities for decision making and other exercises for cognitive and emotional engagement like role-play or voting stations (Pedretti & Navas Iannini, 2020a, p. 75)

As both types of exhibitions overlap (also with more classical pedagogical and experimental exhibition types) and complement each other (Pedretti & Navas Iannini, 2020a, p. 61) in addressing complex issues and their relationship to socio-cultural, political, environmental, and ethical considerations (Navas Iannini & Pedretti, 2022, p. 5), both exhibition types will be collectively referred to as "modern SSI-exhibitions" throughout this dissertation. Due to their theoretical emphasis and design approach these exhibitions have the potential to engage their visitors in complex socio-scientific issues and enable them to acquire skills that can empower them for social, environmental, and political change (McGhie, 2020;

Pedretti & Navas Iannini, 2020a; Sutton 2020), and thus have the potential to foster their critical scientific literacy. In addition, their dialogical communication, the inclusion of different social perspectives, and the choice of options offered within modern SSI-exhibitions may also be the key to social environmental identity work as: "It is the mediating function between what's inside and what's outside, between the agent who chooses to act and the structures that provide the opportunities for acting, alternatives among which actions may be chosen, and the consequences of acting. Agency and structure are like the two blades of a pair of scissors that need to work together to do their job. An agent confronts a world—sometimes by visiting a museum—and out of the interaction constructs an image of what kind of person she wants to be, and how she should live her life." (Rounds 2006, p. 137)

From this it can be concluded that a modern socio-scientific exhibition on the energy transition should have a positive effect on students' critical energy literacy.

6. Learning for Critical Energy Literacy in Museums

Learning in the museum is aptly described as free-choice learning (Falk & Dierking, 2011) This is because visitors are free to decide what they want to look at, for how long they want to look at it, what they want to try out, what they want to discuss with others, and where they want to go next. As such, visitors' free-choice learning is primarily driven by their intrinsic motivations (Falk & Dierking, 2000) and highly dependent on the personal characteristics like their prior knowledge and interests (Falk et al., 2011; Falk & Storcksdieck, 2005). The preconditions for or influences on this kind of learning are therefore many and varied, and their study, as well as the precise characterization of museum learning itself, is an ongoing quest of museum researchers and professionals (Hohenstein & Moussouri, 2018). The "contextual model for learning" describes the experience of a museum visit as an interplay between the personal, the sociocultural, and the physical context (Falk & Dierking, 2013, p. 27).

But as „highly personal and unique" (Falk & Storksdieck, 2005, p. 123) learning in museums always will be, it still can be assumed in general that "the better the additional concepts and ideas are connected to the visitor's prior knowledge and previous experiences" (Bamberger & Tal, 2008, p. 4), the more significant the learning experience is perceived to be.

Modern SSI-exhibitions, as already mentioned, deal with very complex questions without satisfying conclusions and usually do so in unconventional forms of presentation, which often require a particularly active engagement. They might therefore not only benefit from a good fit between their content and prior knowledge and interest, but even depend on it, as they might simply overwhelm if the fit is too poor. The ability of an exhibition on the energy transition to promote critical energy literacy among students may thus depend highly on its fit with their prior school knowledge and interests.

6.1 Conceptual Energy Knowledge

There is a broad consensus that students need a deep understanding of energy in order to understand and assess the socio-scientific issues around climate change and energy (Chen et al. 2014). Consequently, energy is anchored as a basic and crosscutting concept in science education (National Research Council, 2012; OECD, 2019) that includes conceptual knowledge about energy forms and sources, energy transfer and transformation, energy degradation, and energy conservation (e.g., Duit & Neumann, 2014). It is assumed that with an understanding of these concepts and with "practice applying them to authentic problems related to energy resources, students are well positioned to develop the kind of energy literacy that is critical for tomorrow's citizens and scientists" (Chen 2016, p. 137). In this way, conceptual energy knowledge can be seen as a foundational element of critical energy literacy that can be taught in a way that prepares students to become energy literate in a V-I scientific literacy sense but that at the same time also should prepare students for future learning opportunities and participation in the energy discussion regarding the transition towards a sustainable energy system.

Following this idea, conceptual energy knowledge should be helpful for students to face real-life problems and learn new information when they have access to high-quality resources such as modern SSI-exhibitions on the energy transition. Taking this a step further, students with higher levels of knowledge should be able to maneuver through such an exhibition more easily and may be better able to construct new knowledge from it. In addition, although it has already been discussed, that content knowledge alone rarely leads to behavioral change (see Section 4.2.1), and therefore conceptual energy knowledge alone is unlikely to lead to the desired behavior, it could still be very useful in the sense that it helps students evaluate information about the impact that energy-related behaviors can have on climate change and resource scarcity. To date, however, there seems to be little to no empirical evidence to support the assumption that conceptual energy knowledge is actually useful for students in developing critical energy literacy. In fact, it is known that knowledge per se does not make informed decision-makers (Falk & Dierking, 2010) and that students' level of energy knowledge is fundamentally a cause for concern (e.g., Herrmann-Abell & DeBoer, 2017).

Thus, modern SSI-exhibitions on the energy transition are not only potentially appropriate learning environments for developing critical energy literacy in students but also, because of the free-choice nature of learning in these exhibitions, an excellent testing ground for the hypothesis that conceptual energy knowledge is indeed helpful to students in navigating these complex, multi-perspective exhibitions. This conceptual knowledge connection is particularly valuable because 1) school-based education has a strong focus on conceptual energy knowledge, and 2) unfortunately for educational research, Bell's observation that "research on schools rarely builds on findings from research in informal settings and vice versa" (Bell, 2009, p. 18) still holds true.

6.2 Topic Interest

For learning to occur and to be effective, students must be motivated to engage with the learning environment and content. While school has strong external incentives, free-choice learning in museums depends mainly on intrinsic motivation (Falk & Dierking, 2000). Although out of school learning environments such as museum exhibitions are known to foster personal interest and motivation in visitors (Lewalter et al., 2021), visitors also bring varying levels of individual interest with them when they enter an exhibition. Individual interest then likely influences how they engage with the exhibition - and how they learn within it (Harackiewicz et al., 2016).

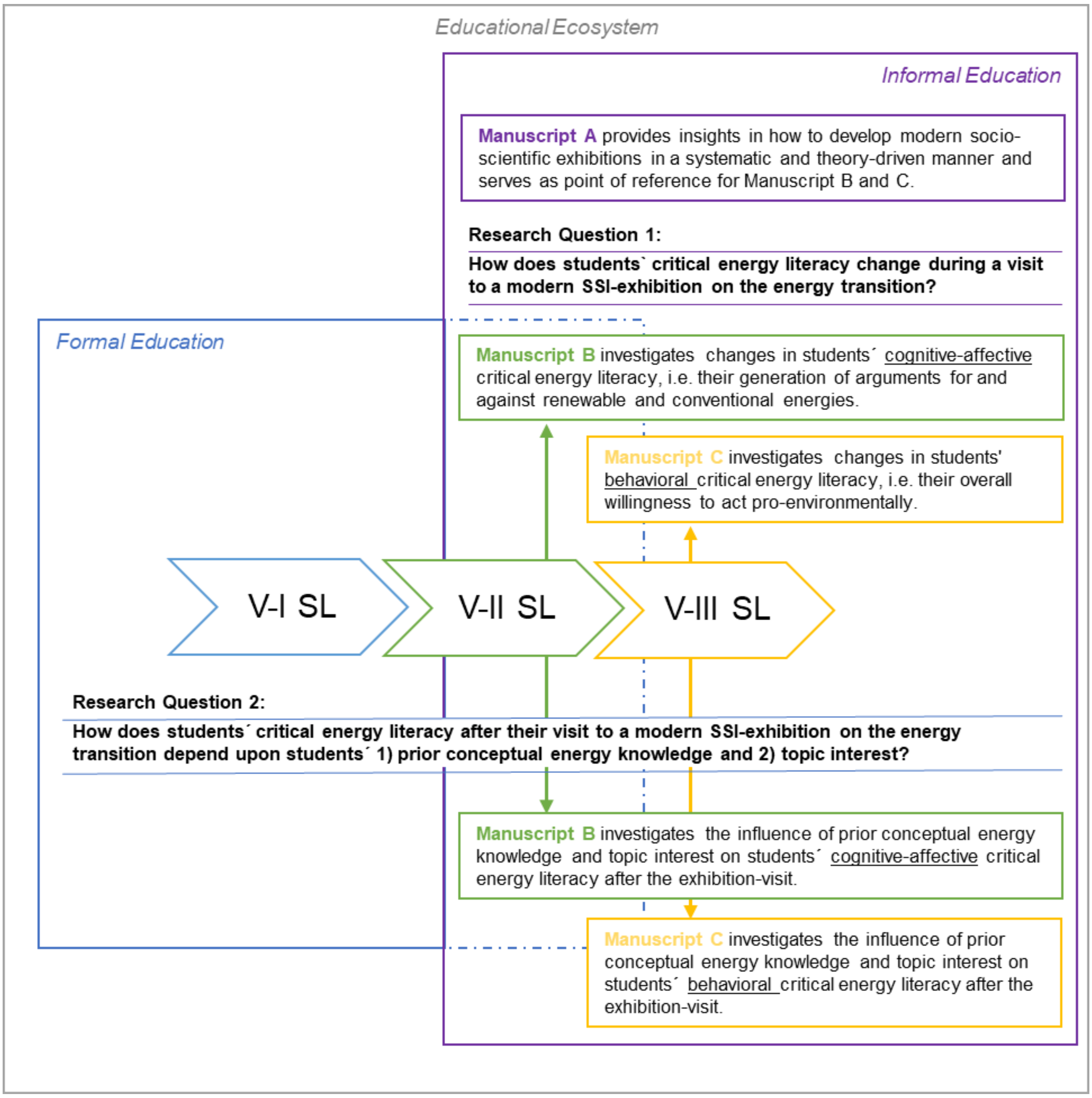
Indeed, interest is known to be closely related to learning: It increases attention, focus, and enjoyment when engaging with a topic and facilitates learning through higher engagement (Renninger & Hidi, 2016). This is particularly true for learning in informal contexts (Barriault, 2014, p. 14), and even more so for the free-choice learning that occurs in museum exhibitions, which is often driven by the visitor's interest in the subject matter conveyed by the exhibition. Moreover, choosing what to engage with and to what extent during the exhibition visit is also shaped by interest. Thus, individual interest in a topic can be seen as a fairly stable predisposition that manifests in the moment as situational interest in response to the affordances and characteristics of the learning opportunity (Harackiewicz et al., 2016). At the same time interest in the energy transition can be seen as a measurement for students´ positive inclination and attitude towards energy conservation or the sustainable use of energy sources (see Section 3.3) and therefore qualifies in itself as a foundational element of critical energy literacy or energy literacy in a V-I scientific literacy.

Students' interest in the energy transition is therefore identified as an important motivational prerequisite for student´s engagement with the learning environment under study and thus their development of critical energy literacy through a modern SSI-exhibition on the energy transition.

7. Research Questions

Combining the inherent strengths of school teaching and modern exhibitions on social-scientific issues could be a complementary approach to preparing students in a holistic and reasonably time-efficient way for the major challenges they will face in their lives. However, at present it is not known whether these exhibitions are actually as successful as can be assumed from the theoretical considerations (see Section 4 and Section 5), nor to what extent school-based knowledge as currently taught and students´ topic interest prove useful for learning in such exhibitions. This dissertation explores these questions in relation to the pressing socio-scientific issue of the energy transition, that depends on a critically energy literate society.

The following graph sums up the research question this dissertation is therefore investigating and provides an overview about what part of critical energy literacy was investigated in what manuscript of this dissertation. The associated hypothesis that were formulated in the view on the acquisition of critical energy literacy and museum learning presented before, can be found in the respective study summaries (see Section 9).



8. Material and Methods

8.1 The *energie.wenden* Exhibition – Manuscript A

Manuscript A presented the modern SSI-exhibition *energie.wenden,* that was developed at the Deutsches Museum in Munich, to an international audience. The article communicates the goals of this special exhibition, its conception and content, as well as first impressions of its use by visitors. Thereby Manuscript A describes the treatment investigated in the subsequent studies of this dissertation in its full complexity and provides insight into how the key elements of SSI-learning environments, like perspective taking and the opportunity for socio-scientific reasoning (see Section 4.1.1), were purposefully integrated in the agential design of the exhibition and how that design also provides visitors with opportunities for identity-work (see Section 4.2.2) through the engagement with its central interactive format.

The article begins by stating that the energy transition is a complex process involving society as a whole, and that the curators of the exhibition have set themselves the task of presenting precisely this process and the trade-offs involved, to motivate visitors to actively engage critically with the issue, and ultimately to increase the visitors' competence and willingness to participate in the overall societal process of the energy transition, thereby aiming at the objectives of modern SSI-exhibitions (see Section 5.2).The fact that the challenge here lies primarily in the necessary multi-perspectivity in dealing with this important topic is also presented right at the beginning. To meet these goals and challenges, the exhibition curators have given the socio-scientific issue of the energy transition a central innovative interactive format that gives visitors plenty of opportunity to practice perspective taking, socio-scientific reasoning and decision making (see Section 4.1) and, with the help of the designers, developed a clear, structured and systemic exhibition design, which culminated in said format.

In addition to the exhibition's prologue and epilogue, this manuscript discusses in detail the exhibition's nine thematic rooms, which use various interactive elements to illuminate the particular crucial points and emotional challenges of each area with regard to implementing a global energy transition and provide insights into different approaches to solutions and ecological, political and socio-technical contexts. Although these overarching thematic rooms could also be visited individually, they were systematically linked by the exhibition's central interactive format and also served as "knowledge repositories" for this format.

There, at the heart of the exhibition, visitors were asked to take on the role of policymakers and design their own personal energy transition. Taking on this overviewing role, was thought of as allowing especially adolescent visitors, the target audience of this exhibition, to visit the topic of the energy transition from a perspective that enables them to engage with all areas of this societal undertaking, including those that might initially be considered out of their range in their role of students. As "politicians", visitors then encountered various stakeholders of the energy transition who approached them with their personal concerns and aspirations and urged them to make energy policy decisions in their favor. In order to objectify these relevant and realistic but identity-laden demands, visitors were then able to visit the corresponding thematic rooms in order to use them as knowledge repositories for their reasoning process and choose an energy policy measure that suited them at the respective decision station. The moment they chose one of the three possible measures, potential voters from different backgrounds appeared on the screen of these stations to express their additional personal views on each and every one of those measures. Visitors had to weigh all these perspectives and arguments in order to find their own position towards the respective challenge and decide accordingly. At the end of the exhibition visit, the evaluation of these decisions resulted in the assessment of visitors' own energy transition-profile, providing a synopsis of all their decisions and what those in combination said about their "energy transition-type" or politician-identity. Visitors were then able to compare these results with each other and see how the, with a wink of the eye formulated, "energy transition-types" matched their own (previous) perceptions of themselves. Finally, visitors could compare their energy policy choices with the entirety of the choices made by all visitors of the exhibition up to their visit date.

Taken as a whole, the exhibition provides visitors with systemic insights into the societal process of the energy transition (see Section 3.1) and a wide range of measures to promote the energy transition including direct and indirect, individual and collective behavior in the areas of consumption, housing, mobility, energy production, and transportation, as well as participation in energy policy discourse (see Section 4.2).The article ends with an overview and a first analysis of the decisions made by the visitors and the distribution of the energy transition profiles assigned so far. It becomes clear that the decisions made were not overly dependent on the opinions of the main players in the energy transition. This can be seen as a first indication that the visitors actually seemed to weigh the multitude of solutions, perspectives and personal viewpoints presented in the exhibition and/or at least matched them with their own perspectives and personal identities.

In conclusion, Manuscript A provides the necessary foundation for linking the findings of the subsequent research to this theory-based, highly complex, intertwined, and rich learning experience.

8.2 Study Design and Participants

Manuscript B and Manuscript C, included in this dissertation, are two studies that emerged from an overall study that aimed to answer the previously stated research questions (see Section 7) by comprehensively investigating the learning environment described in Manuscript A.

This overall study was approved by the Bavarian Ministry of State for Education and Culture, Science and Art before it was conducted (Data collection took place from September 2017 to November 2017) and followed a pre-post-design in which students were given a pen and pencil-test one week before (T1) and one week after (T2) their visit to the exhibition. Testing took place at school and was consented to by a legal guardian of the students. All tests were conducted, explained, and supervised by the first author. Before their 90-minute visit, students received a brief introduction to the exhibition as regular visitors would have received by the exhibition`s host upon entering the exhibition.

Students were explicitly told that they were free to use the exhibition as they saw fit and that they could decide for themselves whether or not to participate in the interactive format. Students then visited the exhibition in the intended free-choice form and chose to do so in pairs, small groups or alone. The respective formations could change during their visit. Teachers were invited to visit the exhibition as their students did but had no influence on how their students interacted with the exhibition.

The overall study was conducted in Bavaria, Germany. 10 classes from five secondary schools, from grades eight to ten, participated in it with a total of N = 222 students. For the analyses conducted in Manuscript B as well as Manuscript C, only students who attended the exhibition-visit and had data from the pre-and post-test were considered. The final data set consisted of 185 students (166 from 8th grade Gymnasium, and 19 from 10th grade Realschule). The ages of these students varied from 12 to 17 years, with an average 13.58 years (SD = 1.06), and gender distribution was approximately equal (42.2% female, 57.3% male, 0.5% gender neutral).

8.3 Instruments and Variables

The instruments included a knowledge test, scales, and open-ended questions. Two sets of outcome variables were derived from these instruments: "arguments regarding conventional and renewable energies" (i.e., cognitive-affective critical energy literacy, Manuscript B) and "overall willingness to act" (i.e., behavioral critical energy literacy, Manuscript C). The instruments used to measure changes in these elements from before to after the exhibition visit were included in both the pre- and post-tests of the overall study. The instruments from which the independent variables for both studies (Manuscript B & C) were derived, namely students' "conceptual energy knowledge" and "interest in the energy transition", were only included in the pre-test, as they were not expected to change during the exhibition to warrant inclusion in the post-test.

To capture changes in students' cognitive-affective energy domain, Manuscript B incorporated open-ended items into the study´s pre- and post-test to get insights into students´ understanding “of the social, environmental, political and economic challenges, benefits and impacts of various energy sources, developments and technologies” (Lowan-Trudeau &

Fowler, 2021, p. 2). This understanding was captured with one open-ended item each for renewable and conventional energy sources, which required students to generate arguments for and against these energy sources (after Knipfler, 2008; Toplak & Stanovich, 2003). These arguments in the sense of “reasons” do provide learners with an initial overview and can be used to measure a level of understanding (Böttcher et al., 2016). Three variables were derived from the responses for each open-ended item: the overall number of arguments; the number of pro arguments; and the number of contra arguments. In addition, the student responses were analyzed qualitatively to gain insight into possible changes in the students' thematic focus. This instrument was designed to show the extent to which the students' knowledge of the many facets and systemic scope of the energy transition, as well as their weighing of the advantages and disadvantages of using and deploying different energy sources and technologies, may have been deepened after visiting the exhibition.

In order to detect changes in students' behavioral domain of critical energy literacy Manuscript C assessed a wide variety of students´ behavioral intentions that are relevant to the acceleration of the energy transition in the study´s pre- and post-test. For this, sixteen items of a pre-existing instrument, that Boyes and colleagues developed to evaluate students’ willingness to act in several areas of the energy transition, and in which they took political, situational, financial, and personal factors into account (Boyes et. al 2009), were chosen. These items ranged from statements that students would be willing to “switch things off at home” in order to save energy or to use low emission transportation even if it was more inconvenient for them to their inclination to “vote for a politician who said they would bring in laws to reduce global warming, even though it would stop me doing some of the things I enjoy”. Students ´willingness to act was measured on a five-point Likert scale asking in how far they agreed with these sixteen statements ranging from "not at all" to "very much". Since the present research was primarily interested in fostering a general tendency to act pro-environmentally through a holistic learning environment, rather than investigating the extent to which concrete information influences students' willingness to act in a particular area, an average of all items was calculated to gain insight into students' willingness to act as a general tendency.

To gain insight into students' conceptual energy knowledge (Chen et al., 2014; Nordine, 2016; U.S. Department of Energy, 2017), a single-choice test was included in the pre-test of both studies. This test was an abbreviated version of an established instrument to measure secondary students' conceptual knowledge of energy (Energy Concept Assessment, ECA by Neumann et al., 2013). From this established test-instrument, 24 items were chosen, based on their closest content relationship to the energy transition, their balanced representation of the four key ideas about energy (e.g., Duit & Neumann, 2014), and their level of difficulty for each of the key ideas.

Students' topic interest was measured as students' interest in the energy transition with four items based on Krapp (2002) in the pre-test of both studies. Students were asked how much they agreed with statements such as "I am interested in the topic of energy transition” or "Engaging with the issue of the energy transition is personally meaningful to me." All items were measured on a five-point Likert scale ranging from "not at all" to "very much".

A more detailed description of the instruments, their piloting, coding, and reliabilities can be found in the original papers of Manuscript B & C (see also the respective appendices).

8.4 Data Analysis

In order to answer this dissertation´s research questions, three statistical tools were used, namely PSPP (Free Software Foundation, PSPP Version 1.6.2.), SPSS (IBM SPSS Statistics, Version 26) and R (The R Project for Statistical Computing, Version 3.1.0.)

To examine the extent to which students' critical energy literacy changed from before to after their visit to the exhibition (R.Q.1), a series of Wilcoxon signed-rank tests were performed because the dependent variables of the study were not normally distributed at T1 and T2.The test can be described as the paranormal equivalent to the t-test, which is highly sensitive towards a violation of the assumption of normal distribution, and is used to determine whether the central tendencies of two dependent samples are different by comparing rank orders at two time points.

The second set of research questions regarding the influence of conceptual energy knowledge and topic interest on students' critical energy literacy after their visit to the exhibition (RQ 2) was investigated using stepwise multiple linear regressions for students’ cognitive-affective and behavioral critical energy literacy after their visit (T2), with students’ prior (T1) cognitive-affective and behavioral critical energy literacy to act as the control variable and students’ prior interest in the energy transition and prior conceptual energy knowledge (T1) as independent variables.

Manuscript B additionally explored the influence of students´ prerequisites for the development of critical energy literacy in a modern socio-scientific exhibition on the energy transition further by applying Necessary Condition Analysis (NCA, Dul, 2016, Dul et al., 2020). Supplementary to the multiple linear regression analysis, which indicates the average influence of a variable on an outcome (and draws a regression line through the middle of the data), the NCA draws a *ceiling line* above the data and finds out what value of x is necessary (but not sufficient) to achieve a certain level of y (Dul, 2016) and is therefore able to detect potential thresholds of conceptual energy knowledge and topic interest that might be essential for students´ learning in complex SSI-learning environments. The NCAs were calculated for parts of students´ cognitive-affective critical energy literacy (T2) that, according to the results from the previously performed stepwise multiple linear regression analyses, depended on either conceptual energy knowledge, topic interest or one of the control variables (= dependent variables, T1). As independent variables for the NCA, the respective T1 values, interest and conceptual energy knowledge were included in the analysis to get further insight into whether a certain level of conceptual energy knowledge and/or topic interest is necessary for students' gain in critical energy literacy after visiting the exhibition.

To reduce the likelihood of false-positive results (type I error), the Bonferroni correction was applied to all analyses in both manuscripts. For a more detailed description of the statistical analysis, please refer to the respective manuscripts.

9. Study Summaries

Both Manuscripts B and C focus on investigating the potential promotion of student´s critical energy literacy through a modern SSI-exhibition on the energy transition, and the impact that students´ prior conceptual knowledge and topic interest might have on said promotion (see Section 6.1 and 6.2). Despite their shared theoretical background and the common objective to find out more about how to effectively and successfully communicate the importance and challenges of the energy transition and foster participation in it, both studies focus on different aspects of critical energy literacy and have different emphases in their argumentation and assumptions questions.

9.1 Manuscript B

Manuscript B focuses on investigating the development of students' cognitive-affective domain of critical energy literacy. Specifically, the aim of this study was to examine the extent to which an interactive socio-scientific exhibition – qualifying as an “agential exhibition” (Pedretti & Iannini 2020a) - fosters cognitive-affective critical energy literacy. Further, the extent to which students’ cognitive-affective critical energy literacy after the exhibition visit depends on their prior conceptual knowledge of energy (Neumann et al., 2013) and topic interest (after Krapp, 2002) was tested.

For Manuscript B, the following assumptions were formulated:

- *Hypothesis 1.a:* The exhibition visit will have a positive impact on students´ cognitive-affective critical energy literacy.
- *Hypothesis 2.1.a:* Students’ conceptual energy knowledge prior to their exhibition visit positively influences gains in students´ cognitive-affective critical energy literacy.
- *Hypothesis 2.2.a:* Students’ topic interest in the energy transition prior to their exhibition visit positively influences gains in students´ cognitive-affective critical energy literacy.

With regard to *Hypothesis 1.a*, the results of Wilcoxon signed-rank tests showed that students' overall number of renewable energies-arguments did not significantly change in comparison from before to after the exhibition visit. However, the (smaller) proportion of arguments *contra* renewable energy increased significantly (z = -3.516, p = <.001, r = .27).

Supplemented by findings of the qualitative data analyses, these results showed that students stated significantly more (and more specific) aspects of renewable energy and its use that they rated as *negative* or difficult after their exhibition visit. In contrast, for students` conventional energies-arguments, it was found that their *overall* number was significantly higher after visiting the exhibition (z = -2.834, adj. p = .007, r = .21), and that this gain was due to the significant increase in both portions of *pro- and contra*-arguments. Supplemented by the results of the qualitative analysis of students' arguments, these results showed that students were able to identify significantly more *negative as well as positive* aspects of conventional energy sources (in the current energy system) after visiting the exhibition than before. All in all, these findings were interpreted in a way, that by visiting the agential exhibition, students were able to increase their cognitive-affective critical energy literacy (see Section 10.1).

Regarding *Hypothesis 2.1a* and *2.1b* study findings of stepwise multiple linear regression analyses showed that conceptual energy knowledge, but not topic interest, acted as a prerequisite to the acquisition of parts of students cognitive-affective critical energy literacy (T2) when controlled for students cognitive-affective critical energy literacy (T1). The study found that conceptual knowledge significantly influenced students' arguments *pro* conventional energies (β = .24, p < .001).and arguments *contra* renewable-energies (β = .20, p = .007) after their exhibition visit, with robust effects when controlling for the respective T1 values. The necessary condition analysis (NCAs), that were conducted for these two outcome variables of students ´cognitive-affective critical energy literacy, and included conceptual energy knowledge, topic interest and respective T1 values as independent variables, found that conceptual energy knowledge indeed was a *necessary* condition for students to generate a meaningful number of arguments for conventional energy sources (T2) but not against renewable energies (T2). Here, an above average level of contra arguments regarding renewable energies at T1 proved to be a necessary condition for a high T2 value of arguments contra renewable energies after their exhibition visit. However, while conceptual energy knowledge did indeed prove to be a necessary condition for students to generate *any* pro conventional energies-arguments at all after their exhibition visit (for this to occur, students had to visit the exhibition with a score of 0.175 on the conceptual energy knowledge test, to be able to generate more than 2.4 arguments pro conventional energies at T2, a score of 0.218 in the prior knowledge test was required), the NCA results also showed that students needed to solve only 20% of items on the conceptual energy knowledge test correctly (on average, students solved 48% of the items correctly) in order to substantially increase their arguments about conventional energies.

In conclusion, these results demonstrate the effect that modern SSI-exhibitions can have on students´ critical scientific literacy and importance of conceptual knowledge in global curricula. They also show that a successful exhibition design should consider school knowledge and contribute to answering the open question of "in what ways school-based learning is substantially transferred to out-of-school life" (Bransford et al. 2006, p. 216). More importantly, the findings show that this learning activity is meaningful even for students with below-average prior conceptual knowledge of energy, and also for students who were not especially interested in the energy transition before visiting the exhibition. These findings could be related to the highly motivating novelty of this kind of exhibition (see Section 10.2 and 10.3) and are consistent with the description of SSI-learning environments as "ideal contexts for bridging school science *and* students' lived experience" (Sadler, 2011, preface), and strengthens the case for improving collaboration between formal and informal education.

9.2 Manuscript C

The second study and third contribution to this dissertation, Manuscript C, focuses on investigating the development of students' behavioral domain of their critical energy literacy through an interactive socio-scientific exhibition on the energy transition. The first goal of this study was to investigate whether students' behavioral critical energy literacy changed positively during their relatively short visit to the exhibition. Second, the study aimed to investigate the role of students' prior conceptual knowledge about energy (Neumann et al., 2013) and interest in the energy transition (after Krapp, 2002) to learn more about the promising synergistic use of informal and formal learning venues in preparing students for the challenges of the 21st century. The following assumptions were tested as part of Manuscript C:

- *Hypothesis 1.b:* The exhibition visit will have a positive impact on students' behavioral domain of critical energy literacy.
- *Hypothesis 2.1.b:* Students’ conceptual energy knowledge prior to their exhibition visit positively influences gains in students' behavioral domain of critical energy literacy.
- *Hypothesis 2.2.b:* Students’ topic interest in the energy transition prior to their exhibition visit positively influences gains in students' behavioral domain of critical energy literacy

Regarding *Hypothesis 1.b*, results of Wilcoxon signed-rank tests showed that students’ overall willingness to act increased significantly, from prior to after their exhibition visit ($z = -2.418$, $p = .016$, $r = .18$). In addition, further analysis strongly suggested that this increase was indeed due to a change in students´ actual overall behavioral tendency, and not just changes in a few specific behavioral intentions, as individual Wilcoxon signed-rank tests for all 16 items showed only three significant changes (including one with a negative effect) in terms of individual behaviors, but several more items with more positive than negative ranks. This means that this change in overall behavioral tendency cannot be attributed to individual behaviors, but only appears in its entirety These findings support the theoretical considerations that modern SSI-exhibitions are indeed a successful tool for fostering students´ behavioral critical energy literacy. However, regarding the findings of Manuscript C, it is important to note, that despite the overall positive result, 37% of the students were less willing to act pro-environmentally after their visit to the exhibition than before.

With regard to *Hypothesis 2.1.b & 2.2.b* the results of stepwise multiple linear regression showed, that after including prior overall willingness to act as control variable, only students' conceptual energy knowledge still contributed significantly to overall willingness to act at T2 (β = .13, $p < .01$) and explained an additional 1% of variance after controlling for prior overall willingness to act (T1). The positive effect of interest in the energy transition on overall willingness to act T2 (β = .25, $p < .01$) vanished when controlling for overall willingness to act T1 (β = .02, p = .76). Regarding the interpretation of this second finding it is important to note that interest already was moderately correlated to prior overall willingness to act (T1). The first finding aligns well with the assumption that conceptual energy knowledge could be useful for interpreting the complex, systemic, and interdisciplinary information students received during their exhibition visit (Chen et al., 2014), and the important role that conceptual energy knowledge should play in the development of (critical) energy literacy (Chen et al, 2014; Nordine, 2016; U.S. Department of Energy, 2017). The fact that topic interest did not show any effect on the changes in students´ overall willingness to act pro-environmentally might be due to situational factors during students´ exhibition visit and the motivational aspects of the novel learning environment (see Section 10.2 and 10.3). The results therefore also show that further research is needed to shed light on interindividual differences in how people perceive and use information (Longnecker, 2016), and their response to exhibitions on complex SSI topics particularly in museums, in a way that broad audiences are able to make use of it (Lackner et al., 2019).

In conclusion, Manuscript C revealed that the exhibition approach to promoting the behavioral domain of critical energy literacy is promising, and can be useful for museums that want to motivate people to act to address "identity" in their exhibitions and to create explicit points of connection for its further development. It also showed that conceptual knowledge as acquired in school is beneficial for the use of free-choice learning activities in socio-scientific contexts and that successful exhibition design does well to take school knowledge into consideration. Thus, the findings of this study may further support the synergistic use of formal and informal learning venues.

10. Discussion

The overall goal of this dissertation project was to gain a better understanding of the potential for promoting critical energy literacy through the holistic learning environments of modern SSI-exhibitions on the energy transition, and if these exhibitions might complement formal education in its goal of providing students with Vision II/-III -scientific literacy. By including both students' prior conceptual knowledge of energy and their interest in the topic as independent variables, this research attempts to 1) bridge the gap between formal and informal education and also 2) investigate the extent to which more foundational elements of an energy literacy that can be interpreted in a Version I sense influence students' development of critical energy literacy in a Vision II/-III manner. Overall this dissertation project aimed at adding to the research base on the extent to which school-based knowledge and interests help students navigate complex SSI-learning environments, and how combining the inherent strength of informal and formal learning sites might best help students meet the challenges of the 21st century.

10.1 The Development of Students´ Critical Energy Literacy

The first research question of this dissertation project was in how far modern SSI-exhibitions on the energy transition helped students to develop critical energy literacy, in a way that helps them become able and willing to partake in the urgent socio-scientific issue of the energy transition.

The first study conceptualized energy literacy in a Vision II sense and measured changes in the cognitive-affective domain of students´ critical energy literacy via their generation of arguments for or against the usage of renewable and conventional energies. With regard to this dissertation´s first research question, Manuscript B found that students' overall number of renewable energies-arguments did not change in comparison from before to after the exhibition visit. However, the proportion of arguments *contra* renewable energy increased significantly, meaning that after their exhibition-visit, students stated significantly more aspects of renewable energy and its use that they rated as negative or difficult. In contrast, for students` conventional energies-arguments, the study found that their *overall* number was significantly higher after visiting the exhibition, and that this growth was due to the significant increase in both *pro- and contra*-arguments. Thus, students were able to identify significantly more negative as well as positive aspects of conventional energy sources after visiting the exhibition than before.

At first glance, the results seemed to contradict a successful intervention in favor of the energy transition, since students learned more negative aspects about renewable energies and positive aspects about conventional energies and their use. But a closer look at the data revealed that 1) students entered the intervention with a higher level of knowledge about the positive aspects of renewable energies, and 2) even after the intervention, they provided on average many more arguments in favor of renewable energies than in favor of conventional energies. In addition, it was observed that all students were generally in favor of the energy transition both before and after visiting the exhibition. The fact that they seem to have learned more positive facts about conventional energies and more negative aspects of renewable energies "can [therefore] be regarded as a key indicator of conscious opinion formation and reflective judgment" (Knipfler 2009, p. 39), as these facts go against their own biases. And finally, it has to be considered, that the knowledge of the negative aspects of renewable energies and the benefits of conventional energy is ultimately necessary to understand why the energy transition is so complex and challenging, and might actually help a critical energy literate person to address these challenges in a realistic way (Lowan-Trudeau & Fowler, 2021).

Overall, the results of the study indicate that students had a more balanced view of the use of different energy sources and a more differentiated understanding of the advantages and disadvantages of energy sources after visiting the museum exhibition. Therefore, it can be concluded that the modern SSI-exhibition on the energy transition indeed supported students' acquisition of cognitive-affective critical energy literacy.

The second study pushed the conceptualization of critical energy literacy further into a more agency concentrated Vision III sense, by focusing on investigating the development in students` behavioral critical energy literacy. The study found that students' overall willingness to act pro-environmentally increased significantly after visiting the exhibition. This result is particularly valuable because the observed increase actually reflects a change in students' overall behavioral tendency and not just some changes in a few specific behavioral intentions, as Wilcoxon signed-rank tests for all items of students' willingness to act showed.

However, this positive result is somewhat limited by the significant number of students who were actually less willing to act pro-environmentally after visiting the exhibition. There could be several reasons for this, which could either be found in the design of the exhibition, in the personal prerequisites of the students or could have been due to a combination of both. In light of the literature reviewed in the theoretical background of this dissertation (see Section 4.2.1), it might be possible that the complexity of the exhibition may have resulted in some students being overwhelmed. As this can, as already described years ago by Jensen and Schnack (1997), lead to paralyzing and preventing action rather than encouraging it, it might be possible that the exhibition visit dimmed some students' initial assessments of their willingness to act. It may also be that students, during their exhibition visit, have gained a more realistic picture of the effort or cost behind each action and re-assessed their personal capability to do so, and adjusted their willingness to act accordingly (Steg et al., 2014). And indeed, the challenge of presenting complex issues in an understandable and motivating way that does justice to their complexity *without* denying the effort required to address them is well-known in the communication of socio-scientific issues, particularly in the context of climate change (Howarth et al., 2020; Moser, 2016). Therefore, while overall the investigated approach of the exhibition as well as the novel use of the willingness to act items (Boyes, 2009) to measure student behavioral tendency to act pro-environmentally seems promising, it also becomes clear that further research regarding interindividual differences in how people perceive and use information in exhibitions (Longnecker, 2016) on complex SSI topics is needed. This knowledge will further support future efforts to communicate such complex SSI topics, particularly in museums, so that they can be used by a wide range of audiences (Lackner et al., 2019).

Still, the combined results of Manuscript B and Manuscript C are overall consistent with the theoretical assumption that a modern SSI-exhibition on the energy transition, that gives students a sense of agency and provides them with opportunities for perspective taking, socio-scientific reasoning and identity work promotes students' critical energy literacy in a Vision II/-III sense. Additionally, it is also worth noting that the small to moderate effects, that can be observed in the changes of students ´critical energy literacy from before to after the exhibition visit, are remarkable for the 90-minutes students visited the exhibition.

10.2 The Influence of Conceptual Energy Knowledge and Topic Interest

Findings of both studies showed, that conceptual energy knowledge, but not topic interest, acted as a prerequisite to the acquisition of critical energy literacy in a modern SSI-exhibition on the energy transition, when controlled for T1 values of students' critical energy literacy.

As previous research has shown that learning experiences in exhibitions are generally perceived as more meaningful when the fit between the exhibition and the personal characteristics of the visitor is high (Bamberger & Tal, 2008, p. 4), it can be assumed that students with higher conceptual energy knowledge were better able to make use of the exhibition, resulting in the development of their critical energy literacy. This ties in well with the assumption that conceptual energy knowledge might be generally useful for interpreting the complex systemic and interdisciplinary information regarding the energy transition in SSI-learning environments (Chen et al., 2014) or even necessary, as conceptual energy knowledge was also identified as a necessary condition for students to generate a meaningful number of arguments for conventional energy sources after their exhibition visit via NCA. From an identity perspective, the effect of conceptual energy knowledge could also be interpreted in the way, that students who acquired more conceptual energy knowledge in school were more likely to have seen themselves as an "energy person" from the start (Brickhouse et al., 2000; Hazari et al., 2022). In both cases, students would have felt more competent during their exhibition visit in dealing with energy transition-related information and in their role as actors in the energy transition.

Overall these findings are in line with evidence on the importance of prior knowledge in learning (e.g. Bransford, 2000; National Academies of Sciences, Engineering, and Medicine, 2018) and assumptions about the prominent role that conceptual energy knowledge should play in (critical) energy literacy (Chen et al., 2014; Nordine, 2016; U.S. Department of Energy, 2017), and indicate that conceptual knowledge as acquired in school is beneficial and important for making use of free-choice learning activities in socio-scientific contexts for instance in museum exhibitions. However, the results of the NCAs conducted in Manuscript B also showed that students only needed to correctly answer about 20% of the items on the conceptual energy knowledge test to significantly improve their arguments about conventional energy. In other words, only those students at the very low end of conceptual energy knowledge (which was about 8% of the participants) had difficulty using the exhibit in a way that increased their critical energy literacy in *all* measured outcome variables.

The fact that neither study did detect any influence of prior topic interest on students´ change in critical energy literacy during their exhibition visit is not consistent with previous research that typically identifies individual interest as a good predictor of engagement and learning in corresponding learning environments (Carman et al., 2021; Krapp, 2002; Renninger & Hidi, 2016). This finding might be due to a set of reasons: First, it seems possible that in this dissertation´s data the lack of effect for interest on students´ behavioral critical energy literacy might be due to interest being moderately correlated to prior overall willingness to act (T1) which was included as a covariate when investigating the effect of interest and knowledge on overall willingness to act after the exhibition (T2) via multiple linear regression analysis. Second, because experiencing situational interest can also directly promote learning by increasing attention and engagement (Harackiewicz et al., 2016, p. 221), students' situational interest in the exhibition, particularly in the exhibition's user-centered interactive game (Duan et al., 2021), may actually have overridden students' prior interest in the energy transition as a topic. As triggers for situational interest are highly personal (Renninger & Bachrach, 2015), students´ engagement and learning in the exhibition, therefore, might be due to the multi-perspective design of the exhibition and its complex yet innovative format arousing students' situational interest, rather than their prior interest in the topic.

In summary, the present study shows that conceptual knowledge is indeed beneficial and important to *some extent* for the use of free-choice learning opportunities in socio-scientific contexts. However, the results also show that learning opportunities such as the modern SSI-exhibition investigated in this dissertation are useful even for students with below-average prior conceptual knowledge, as very little conceptual knowledge was required to understand the exhibition. Overall, this study thus makes a nuanced contribution to answering the open-ended question of "the extent to which school learning transfers substantially to life outside of school" (Bransford et al. 2006, p. 216) while demonstrating that modern SSI-exhibitions can be powerful learning environments that do *not* necessarily or extensively depend on prior school knowledge or topic interest.

10.3 Relations Between Observed Learning and Exhibition Characteristics

It seems that the inclusion of many perspectives on the various topics, the diverse characters, and attitudes represented in the exhibition provided students with a variety of chances to connect new concepts and ideas to their "prior knowledge and previous experiences" (Bamberger & Tal, 2008 p. 4*)*, which aligns well with the findings of the socio-scientific movement. Therein, SSI is described as an "ideal context for linking school science and the lived experience of students" (Sadler, 2011, Preface). Therefore, it can be hypothesized that while conceptual knowledge of energy had some influence on learning in this exhibition, student learning may also have occurred based on relevant prior knowledge that was not necessarily scientific (Feinstein, 2011; Laslo et al., 2011) or through the lens of students' personal, social, and cultural values, which are known to influence decision making on socio-scientific issues (Lee & Brown, 2018).

It can be assumed that this learning via multiple connection points is due to the multi-perspectivity of the exhibition and was further motivated by situational interest and relevance (Carman et al., 2021; Krapp, 1999; Lewalter & Geyer, 2009), which in turn is probably due to the novelty of the exhibition and especially the exhibition game, which crystallizes the multi-perspectivity of the exhibition in a highly engaging way. In that game students visited the topic of the energy transition from a “higher perspective”, aka the politician, which allows them to engage with a wider range of topics than they would in assuming another the role i.e. a power plant operator (who would have to follow an agenda) or as “only” themselves as a young student (which are far too often only thought of as consumer) and obligates them to take different viewpoints and agendas (in particular of their voters) into account. But at the same time students kept their personal identity, allowing them to explore everything from their own viewpoint. Therefore, by taking on the role of an overall competent actor in the energy transition, this game gave students the opportunity to practice socio-scientific reasoning, perspective taking, and decision making (Presley et al., 2013; Sadler et al., 2016), while also shaping and practicing their social environmental identity (e.g., Calabrese Barton et al., 2013; Gonsalves et al. 2021; Stapleton, 2015; Verhoeven et al., 2019) by engaging with different personalities and perspectives on how they, as part of the exhibition and the real world, can positively contribute to the energy transition as important actors themselves.

Finally, it seems critical for initiating change in critical energy literacy that the exhibition provided “knowledge in use” on an individual, collective and political level in a systematic and socio-cultural context *throughout* the whole exhibition, and that during the exhibitions’ game students were not told how to act or judged on their "right" or "wrong" actions, but rather provided with insights into their own position, when it comes to participating in the energy transition (Manuscript A).

Therefore, the results of Manuscript B and Manuscript C provide an evidence-based reflection on the theoretical considerations that had gone into the conception and design of the exhibition, as presented in Manuscript A. These combined findings are an important step forward in understanding *how* modern SSI-exhibitions can play their role in promoting critical energy literacy and scientific literacy in general, and thus effectively complementing formal science education.

10.4 Limitations and Recommendations for Future Research

Although it can be argued theoretically which conceptual elements of the exhibition contributed to the observed change in students' critical energy literacy, the present research does not vary different elements of the exhibition and therefore does not provide empirical evidence for the effectiveness of *specific* design elements. Future studies might include this experimental variation in order to provide more concrete evidence and guide museum practitioners en detáil in designing exhibitions. However, one can argue that isolating one design element to test its singular effectiveness would fall short of the complexity of the learning environment the SSI-exhibition provides. Or, in other words, the design of the exhibition might unfold its effectiveness only as a whole wherein the specific design elements complement one another but singularly do not do anything. Thus, a more promising way forward would be to study how students interact with and make use of specific exhibition elements: Future studies might implement some students' observation during their free-choice exhibition visit in order to gain better insight in how they interact with different design elements. Unfortunately, neither was possible in the context of this study, partly for privacy policy reasons and partly because the sample size required to answer the present research questions did not allow for the personal observation of a sufficiently large group of individual students. With regard to the overall study design, a further limitation is that the data of a follow-up measurement point were not included in the present research.

Operationalizing students' critical energy literacy also brings upon some limitations in terms of deriving information from that specific promotion to promoting overall scientific literacy in the Vision II/-III sense. That is, because these outcomes primarily serve as measures of concrete critical energy literacy and only qualify as proxies for transferable skills such as critical thinking (arguments), that help "students be better prepared to engage in decision-making and position taking relative to SSI other than climate change" (Zeidler et al., 2019) or actual pro-environmental behavior, that only moderately correlates with stated pro-environmental intentions like willingness to act (Gifford & Nilsson, 2014; Kormos & Gifford, 2014). There are excellent studies in the field of SSI that have developed and tested measurement tools for transferable skills i.e. Socio-scientific reasoning (i.e. Eggert & Bögeholz, 2010; Kinslow et al., 2018; Romine et al., 2017). But unfortunately, these seem either to specific when it comes to knowledge regarding the used specific examples to measure students decision making process (i.e. Eggert & Bögeholz, 2009) and therefore not appropriate for the broad informal interventions that are SSI-exhibitions, or to detailed when it comes to measuring the skill itself (i.e. Romine et al., 2017) which cannot be assumed to probable be influenced in that detail by the only ever so brief interventions in the museum.

Furthermore, the present research assumes identity work as the mechanism explaining the observed change of willingness to act prior to after the exhibition. However, this assumption was not tested by including corresponding covariates (e.g., self-efficacy or information derived from interviews). Future studies should remedy that and shed further light on how identity work unfolds when students engage with different elements of an exhibition in an out-of-school free-choice learning environment. In addition, the results of Manuscript C also revealed that considerable number of students showed a decrease in their overall willingness to act pro-environmentally after their exhibition visit. In order to investigate further how far SSI topics especially in museums can best be communicated to a broad audience (Lackner et al., 2019) research on interindividual differences in how people perceive and use information (Longnecker, 2016) in such environments is needed. Therefore, it would be advisable for future studies to include variables that measure more personal characteristics of visitors, as well as instruments that allow measuring the level of engagement, stimulation, or possible overstimulation of visitors during their exhibition visit, and to collect more detailed information about what exactly they did in the exhibition. This could for 1) allow for exploring interindividual differences in how people make use of and react to an exhibition (for instance via cluster analysis), and 2) eventually tie those differences to concrete elements of the exhibition.

Finally, although intentions to act are still the strongest predictors of behavior (Hines et al., 1987), and some of the necessary behaviors to accelerate the energy transition are nearly impossible to observe, future studies could still enhance their measurement of pro-environmental behavior by i.e. including a follow up that extends “beyond the site itself” (Ballantyne & Packer, 2009, p. 5) allowing to investigate in how far the formulated intentions might actually transfer to students’ “real life”.

10.5 Implications for Formal and Informal Education

Despite the above described limitations of this dissertation, the results of the present research are significant to the field of formal and informal education for various reasons. First, there are strong indications that the learning observed in both studies was related to the presentation of a wide variety of perspectives on the energy transition within the exhibition and the novelty of the exhibition´s game, which crystallizes the exhibitions´ multi-perspectivity in a particularly strong way. The indication that the perception of different personal perspectives, as well as addressing the visitor as a complex person, provided sufficiently broad gateways to connect with and develop students' ecological social identity, and practice in socio-scientific reasoning, can provide practical guidance for further exhibition development. For the result shows that it can be beneficial for museums that want to motivate people to act to address "identity" in their exhibitions and to create explicit connecting points for its further development.

While other aspects of the exhibition (see Manuscript A) go hand in hand with the ideas of contextual learning and the SSI movement, but remain time-consuming and eventually difficult to implement in schools, the game offers a large number of perspectives, connections and contents in quite a short time and might serve as a template into which a variety of SSI-topics could be inserted (see also Section 4.3).Therefore, features of the researched modern SSI-exhibition appear not only desirable but also transferrable to new SSI-exhibitions or even formal-learning settings.

In addition, the studies confirm the assumption that conceptual energy knowledge is helpful for learning in complex learning environments without conceptual energy knowledge having to be particularly high in order for this learning to occur. Through the innovative use of the new NCA method in this setting between formal and informal education, this dissertation was able to demonstrate not only an average impact of conceptual energy knowledge on learning outcomes through complex SSI-learning environments, but also the required level of conceptual energy knowledge that students need to achieve (in school) in order to benefit from these (out-of-school) environments. Thus, this study was able to provide evidence for a foundational assumption in educational research, while at the same time qualifying this general assumption somewhat, as the level of conceptual energy knowledge found was actually quite low. Although this result shows how powerful the holistic learning environments of SSI-exhibitions can be, the albeit small influence of conceptual energy knowledge on students' critical energy literacy after their exhibition visit still shows, that successful exhibition design does well to take school knowledge into consideration and thus potentially further supports the synergistic use of formal and informal learning venues.

Finally, this study´s findings align with the description of SSI-learning environments as "ideal contexts for bridging school science and the lived experience of students" (Sadler, 2011, Preface) and further bolster the case for enhancing collaboration between formal and informal education. Considering the competing visions of scientific literacy in school (see Section 2.1) and the difficulties if implementing SSI approaches in formal education (see Section 4.3) this is of great value and importance, as it shows that conceptual energy knowledge, that can be considered a goal of scientific literacy Vision I, also plays an important part in the development of a more progressive vision of scientific literacy. Showing that these learning environments can "elevate" this knowledge and help students to develop it further along the scientific literacy continuum up to the agency focused third Vision.

The evidence that the present research provides for the promotion of critical energy literacy through a modern SSI-exhibition is also of great value for the museum field. Because, although the emergence of critical and agential exhibitions as well as the official declarations (Section 5.1) demonstrate that museums have the potential and the will to "foster the changes the world needs most " (Sutton et al., 2017), many museums are actually still quite hesitant to develop such exhibitions. The reasons for that are varied but have a lot to do with the inherent ambiguity and challenging nature of these exhibitions, that is suspected to lead visitors to experience some dissonance or emotional imbalance (D'Mello & Graesser, 2012; Kapur, 2016) and therefore feared to "undermine the integrity of museums for trusted information and as safe, non-threatening places” (Cameron, 2005, p.216). and "places of entertainment and pleasure" (Pedretti & Navas, Iannini, 2020b, p. 708). In addition, the development of such highly interdisciplinary and interactive exhibition-formats is very costly, complex and suspected to be tied to ephemeral public interest rendering them in the worst scenarios obsolete by the time they are opening (Pedretti & Navas Iannini, 2020a, p. 78).

Therefore, the results of the present research that show that 1) a modern SSI-exhibition does indeed promote students' critical (energy) literacy, and that 2) it does so independently of students` prior topic interest and 3) only partially dependent on students´ prior conceptual (energy) knowledge, may make some of these perceived risks a little less threatening, and may help make it a little easier for museums to find motivation and funding to develop and exhibit these important holistic learning environments.

10.6. Conclusion

The aim of this dissertation project was to gain a better understanding of the potential of the holistic learning environments of modern socio-scientific museum exhibitions on the energy transition to promote critical energy literacy, and to investigate whether these exhibitions in general can complement formal education in its goal of providing students with a Vision II/-III scientific literacy.

The dissertation argued, that providing students with opportunities for perspective taking, socio-scientific reasoning and a setting that enables them to consider their social environmental identity should help them develop their cognitive-affective and behavioral critical energy literacy and that modern socio-scientific museum exhibitions are well suited sites to do so. By investigating the extent to which such an exhibition on the energy transition actually fostered students´ generation of arguments regarding the use of renewable and conventional energies and their overall willingness to act, the present research found that the exhibition was indeed successful in increasing students’ critical energy literacy.

In addition, the present research investigated how these results depended on students' prior conceptual knowledge of energy and interest in the energy transition. These two independent variables were chosen because they 1) are crucial for learning in free-choice learning environments such as modern socio-scientific museum exhibitions, and 2) qualify as foundational elements of energy literacy in the sense of a Vision I scientific literacy, as often targeted in current school education. Results showed that only conceptual energy knowledge influenced students' critical energy literacy after their exhibition visit, and that the level required as a necessary condition for students to develop parts of their cognitive-affective critical energy literacy was rather low. Thus, this dissertation was able to provide evidence for a basic assumption in educational research, while at the same time qualifying this general assumption somewhat and showing that modern SSI-exhibitions can be powerful learning environments that do not necessarily or extensively depend on prior school knowledge or topic interest.

From the results of these two studies, the present research inferred that the observed development of students' critical energy literacy was, in fact, likely the result of key exhibition design elements, the theory-based development of which was presented in the first manuscript of this dissertation. These combined findings are an important step forward in understanding *how* modern SSI-exhibitions can play their role in promoting critical energy literacy and Vision II/-III scientific literacy in general, and thus effectively complementing formal science education.

Because the exhibition design elements and instruments used in this dissertation in a novel way, as well as the application of the necessary condition analysis, are potentially useful in other learning contexts, this dissertation contributes to the further practical development and empirical investigation of learning opportunities to promote complex, multi-layered competencies in the sense of Vision II/-III scientific literacy. Important next steps for further exploration of such learning environments identified in this dissertation include examining interindividual differences in how students perceive and use information, as well as their situational responses to exhibitions on complex SSI topics.

Overall, the results of this dissertation indicate that modern socio-scientific museum exhibitions can indeed promote students' critical literacy in a Vision II/-III sense, and that this seems to occur largely independent of topic interest, while conceptual knowledge seems to be helpful to some extent in the use of such exhibitions. Given the role that conceptual knowledge also plays in Vision I scientific literacy, which is widely followed in schools, modern socio-scientific museum exhibitions do indeed seem to support a gradual development of this knowledge toward a Vision II/-III scientific literacy. Thus, combining the inherent strengths of informal and formal learning venues may indeed be a valuable and time-efficient way to help students meet the challenges of the 21st century.

11. References

Abrahamse, W., & Steg, L. (2013). Social influence approaches to encourage resource conservation: A meta-analysis. *Global Environmental Change*, *23*(6), 1773–1785. https://doi.org/10.1016/j.gloenvcha.2013.07.029

Adams, J., Kenner, A., Leone, B., Rosenthal, A., Sarao, M., & Boi-Doku, T. (2022). What is energy literacy? Responding to vulnerability in Philadelphia's energy ecologies. *Energy Research & Social Science*, *91*, 102718. https://doi.org/10.1016/j.erss.2022.102718

Aikenhead, G. S. (2006). *Science education for everyday life: Evidence-based practice*. *Ways of knowing in science and mathematics series*. Teachers College Press.

Akitsu, Y., Ishihara, Keiichi N., Okumara, Hideyuku, & Yamasue, E. (2017). Investigating energy literacy and its structural model for lower secondary students in Japan. *International Journal of Environmental & Science Education*, *12*(5), 1067–1095.

Allen, L. B., & Crowley, K. (2017). Moving beyond scientific knowledge: Leveraging participation, relevance, and interconnectedness for climate education. *International Journal of Global Warming*, *12*(3-4), 299–312. https://doi.org/10.1504/IJGW.2017.084781

Ballantyne, R., & Packer, J. (2009). Future directions for research in free-choice environmental learning. In J. H. Falk, J. E. Heimlich, & S. Foutz (Eds.), *Learning innovations series. Free-choice learning and the environment* (pp. 157–170). Rowman & Littlefield.

Bamberger, Y., & Tal, T. (2007). Learning in a personal context: Levels of choice in a free choice learning environment in science and natural history museums. *Science Education*, *91*(1), 75–95. https://doi.org/10.1002/sce.20174

Barriault, C. L. (2014). *Visitor Engagement and Learning Beahviour in Science Centers, Zoos and Aquaria*. Dissertation. Curtin University.

Bell, L. (2008). Engaging the public in technology policy: A new role for science museums. *Science Communication*, *29*(3), 386–398. https://doi.org/10.1177/1075547007311971

Bell, P. (2009). *Learning science in informal environments: People, places, and pursuits*. National Academies Press.

Bencze, L., Pouliot, C., Pedretti, E., Simonneaux, L., Simonneaux, J., & Zeidler, D. (2020). SAQ, SSI and STSE education: Defending and extending “science-in-context”. *Cultural Studies of Science Education*, *15*(3), 825–851. https://doi.org/10.1007/s11422-019-09962-7

Białynicki-Birula, P., Makieła, K., & Mamica, Ł. (2022). Energy literacy and its determinants among students within the context of public intervention in poland. *Energies*, *15*(15), 1–20. https://doi.org/10.3390/en15155368

Blasch, J., Boogen, N., Daminato, C., & Filippini, M. (2018). Empower the consumer! Energy-related financial literacy and its socioeconomic determinants. *SSRN Electronic Journal.* Advance online publication. https://doi.org/10.2139/ssrn.3175874

Boer, D., & Boehnke, K. (2016). What are values? Where do they come from? A developmental perspective. In T. Brosch, D. Sander, F. Clement, J. Deonna, E. Fehr, & P. Vuilleumier (Eds.), *Handbook of value: Perspectives from economics, neuroscience, philosophy, psychology and sociology* (pp. 129–151). Oxford University Press.

Bolderdijk, J. W., & Steg, L. (2015). Promoting sustainable consumption: The risks of using financial incentives. In L. A. Reisch & J. Thøgersen (Eds.), *Elgaronline. Handbook of research on sustainable consumption* (pp. 328–342). Edward Elgar Publishing. https://doi.org/10.4337/9781783471270.00033

Bossér, U. (2018). *Exploring the complexities of integrating socioscientific issues in science teaching*. Doctoral Dissertation. *Linneaus University Dissertations: Vol. 304*. Linnaeus University Press.

Böttcher, F., Hackmann, A., & Meisert, A. (2016). Argumente entwickeln, prüfen und gewichten: Bewertungskompetenz im Biologieunterricht kontextübergreifend fördern - Konzeptentwicklung. *MNU Journal*(3), 150–157.

Boyes, E., Skamp, K., & Stanisstreet, M. (2009). Australian secondary students' views about global warming: Beliefs about actions, and willingness to act. *Research in Science Education*, *39*(5), 661–680. https://doi.org/10.1007/s11165-008-9098-5

Bransford, J., Stevens, R., Schwartz, D., Meltzoff, A. N., Pea, R., Roschelle, J., Vye, N., Kuhl, P. K., Bell, P., Barron, B., & Reeves, B. & Sabelli, N. (2006). Learning theories and education: Toward a decade of synergy. In P. Alexander & P. Winne (Eds.), *Handbook of educational psychology* (2nd ed., pp. 209–244). Erlbaum.

Bransford, John, D. (2000). *How people learn: Brain, mind, experience, and school: Expanded edition*. National Academies Press.

Braus, J. (April 2013). *Influencing conservation action: What research says about environmental literacy, behavior, and conservation results.* National Audubon Society.

Brickhouse, N. W., Lowery, P., & Schultz, K. (2000). What kind of a girl does science? The construction of school science identities. *Journal of Research in Science Teaching*, *37*(5), 441–458. https://doi.org/10.1002/(SICI)1098-2736(200005)37:5<441:AID-TEA4>3.0.CO;2-3

Brosch, T., Sander, D. & Patel, M. K. (Eds.). (2016). *Understanding the human factor of the energy transition: Mechanisms underlying energy-relevant decisions and behaviors*. Frontiers Media SA. https://doi.org/10.3389/978-2-88919-880-1

Brounen, D., Kok, N., & Quigley, J. M. (2013). Energy literacy, awareness, and conservation behavior of residential households. *Energy Economics*, *38*, 42–50. https://doi.org/10.1016/j.eneco.2013.02.008

Burke, M. J., & Stephens, J. C. (2017). Energy democracy: Goals and policy instruments for sociotechnical transitions. *Energy Research & Social Science*, *33*(2), 35–48. https://doi.org/10.1016/j.erss.2017.09.024

Burke, P. J., & Reitzes, D. C. (1981). The link between identity and rolep. *Social Psychology Quarterly*, *44*(2), 83. https://doi.org/10.2307/3033704

Calabrese Barton, A., Kang, H., Tan, E., O'Neill, T. B., Bautista-Guerra, J., & Brecklin, C. (2013). Crafting a future in science. *American Educational Research Journal*, *50*(1), 37–75. https://doi.org/10.3102/0002831212458142

Cameron, F. (2005). Contentiousness and shifting knowledge paradigms: The roles of history and science museums in contemporary societies. *Museum Management and Curatorship*, *20*(3), 213–233. https://doi.org/10.1016/j.musmancur.2005.05.002

Carman, J., Zint, M., Burkett, E., & Ibáñez, I. (2021). The role of interest in climate change instruction. *Science Education*, *105*(2), 309–352. https://doi.org/10.1002/sce.21610

Chawla, L., & Cushing, D. F. (2007). Education for strategic environmental behavior. *Environmental Education Research*, *13*(4), 437–452. https://doi.org/10.1080/13504620701581539

Chen, K.-L., Liu, S.-Y., & Chen, P.-H. (2015). Assessing multidimensional energy literacy of secondary students using contextualized assessment. *International Journal of Environmental & Science Education*, *10*(2), 201–218.

Chen, R. (2016). Energy and Natural Ressources. In J. Nordine (Ed.), *Teaching energy across the sciences, K-12* (pp. 125–138). NSTApress National Science Teachers Association.

Chen, R. F. (Ed.). (2014). *Teaching and learning of energy in K-12 education*. Springer.

Chen, S.-Y., & Liu, S.-Y. (2020). Developing students' action competence for a sustainable future: A review of educational research. *Sustainability*, *12*(4). https://doi.org/10.3390/su12041374

Choi, S.-Y., Won, A.-R., Chu, H.-E., Cha, H.-J., Shin, H., & Kim, C.-J. (2021). The Impacts of a climate change SSI-STEAM program on junior high school students' climate literacy. *Asia-Pacific Science Education*, *7*(1), 96–133. https://doi.org/10.1163/23641177-bja10019

Chowdhury, T. B., Holbrook, J., & Rannikmäe, M. (2020). Socioscientific Issues within science education and their role in promoting the desired citizenry. *Science Education International*, *31*(2), 203–208. https://doi.org/10.33828/sei.v31.i2.10

Clayton, S.. (2003). Environmental identity: A conceptual and an operational definition. In S. Clayton & S. Opotow (Eds.), *Identity and the natural environment: The psychological significance of nature* (45-65). MIT Press.

Committee on a Conceptual Framework for New K-12 Science Education Standards, Board on Science Education, Division of Behavioral and Social Sciences and Education, & National Research Council (Eds.). (2012). *A framework for K-12 science education*. National Academies Press. https://doi.org/10.17226/13165

Composto, J. W., & Weber, E. U. (2022). Effectiveness of behavioural interventions to reduce household energy demand: A scoping review. *Environmental Research Letters*, *17*(6), 63005. https://doi.org/10.1088/1748-9326/ac71b8

Coskun, A., Zimmerman, J., & Erbug, C. (2015). Promoting sustainability through behavior change: A review. *Design Studies*, *41*, 183–204. https://doi.org/10.1016/j.destud.2015.08.008

D'Mello, S., & Graesser, A. (2012). Dynamics of affective states during complex learning. *Learning and Instruction*, *22*(2), 145–157. https://doi.org/10.1016/j.learninstruc.2011.10.001

Davis, J. (2012). ESD starts where STEM stops: Integrating the social sciences into STEM. In Yu, S (Chair), *Proceedings of the 2nd International STEM in Education Conference.,* Beijing Normal University, China.

Delmas, M. A., Fischlein, M., & Asensio, O. I. (2013). Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012. *Energy Policy*, *61*, 729–739. https://doi.org/10.1016/j.enpol.2013.05.109

DeWaters, J., & Powers, S. (2009). Development and use of an energy literacy survey. In R. Campbell-Howe (Ed.), *38th ASES National Solar Conference 2009* (paper number 0099). Curran.

DeWaters, J., Qaqish, B., Graham, M., & Powers, S. (2013). Designing an energy literacy questionnaire for middle and high school youth. *The Journal of Environmental Education*, *44*(1), 56–78. https://doi.org/10.1080/00958964.2012.682615

DeWaters, J. E., & Powers, S. E. (2011). Energy literacy of secondary students in New York State (USA): A measure of knowledge, affect, and behavior. *Energy Policy*, *39*(3), 1699–1710. https://doi.org/10.1016/j.enpol.2010.12.049

DeWaters, J. E., & Powers, S. E. (2012). *Improving energy literacy among middle school youth with project-based learning pedagogies: 12 - 15 Oct. 2011, Rapid City, South Dakota*. IEEE. http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6129459

Duan, R. J., Walker, G. J., & Orthia, L. A. (2021). Interest, emotions, relevance: Viewing science center interactive exhibit design through the lens of situational interest. *International Journal of Science Education, Part B*, *11*(3), 191–209. https://doi.org/10.1080/21548455.2021.1938740

Duit, R., & Neumann, K. (2014). Ideas for a teaching sequence for the concept of energy. *School Science Review*, *96*(354), 63–66. http://www.ase.org.uk/journals/school-science-review/2014/09/354/

Dul, J. (2016). Necessary condition analysis (NCA). *Organizational research methods*, *19*(1), 10–52. https://doi.org/10.1177/1094428115584005

Dul, J., van der Laan, E., & Kuik, R. (2020). A statistical significance test for necessary condition analysis. *Organizational Research Methods*, *23*(2), 385–395. https://doi.org/10.1177/1094428118795272

Eggert, S., & Bögeholz, S. (2009). Students' use of decision-making strategies with regard to socioscientific issues: An application of the Rasch partial credit model. *Science Education*, *1*(4), n/a-n/a. https://doi.org/10.1002/sce.20358

Evans, H. J., & Achiam, M. (2021). Sustainability in out-of-school science education: Identifying the unique potentials. *Environmental Education Research*, *46*(20), 1–22. https://doi.org/10.1080/13504622.2021.1893662

Falk, J. H., & Dierking, L. D. (2010). The 95 percent solution: School is not where most Americans learn most of their science. *American Scientist*, *98*, 486-493. http://www.americanscientist.org/ issues/id.87/past.aspx

Falk, J. H. & Dierking, L. D. (2013). *Museum experience revisited*. Left Coast Press. https://www.taylorfrancis.com/books/9781315417851 https://doi.org/10.4324/9781315417851

Falk, J. H., Dierking, L. D. & Adams, M. (2011). Living in a learning society: Museums and free-choice learning. In S. MacDonald (Ed.), *Blackwell companions in cultural studies: Vol. 12. A Compagnion to Museum Studies* (4th ed., pp. 323–339). Wiley-Blackwell.

Falk, J. H., & Storksdieck, M. (2005). Learning science from museums. *História, Ciências, Saúde-Manguinhos*, *12*(suppl), 117–143. https://doi.org/10.1590/S0104-59702005000400007

Falk, J. H., & Dierking, L. D. (2000). *Learning from museums: Visitor experiences and the making of meaning*. *American Association for State and Local History book series*. AltaMira Press.

Farla, J., Markard, J., Raven, R., & Coenen, L. (2012). Sustainability transitions in the making: A closer look at actors, strategies and resources. *Technological Forecasting and Social Change*, *79*(6), 991–998. https://doi.org/10.1016/j.techfore.2012.02.001

Feinstein, N. (2011). Salvaging science literacy. *Science Education*, *95*(1), 168–185. https://doi.org/10.1002/sce.20414

Future Earth. (2020). *Risks perceptions report 2020: First Edition.* Future Earth.

Gamage, K. A. A., Ekanayake, S. Y., & Dehideniya, S. C. P. (2022). Embedding sustainability in learning and teaching: Lessons learned and moving forward. Approaches in STEM higher education programmes. *Education Sciences*, *12*(3), 225. https://doi.org/10.3390/educsci12030225

Gifford, R., & Nilsson, A. (2014). Personal and social factors that influence pro-environmental concern and behaviour: A review. *International Journal of Psychology : Journal International De Psychologie*, *49*(3), 141–157. https://doi.org/10.1002/ijop.12034

Gladwin, D., & Ellis, N. (2023). Energy literacy: towards a conceptual framework for energy transition. *Environmental Education Research*, 1–15. https://doi.org/10.1080/13504622.2023.2175794

Gonsalves, A. J., Cavalcante, A. S., Sprowls, E. D., & Iacono, H. (2021). “Anybody can do science if they're brave enough”: Understanding the role of science capital in science majors' identity trajectories into and through postsecondary science. *Journal of Research in Science Teaching*, *58*(8), 1117–1151. https://doi.org/10.1002/tea.21695

Guenther, C. L., Wilton, E., & Fernandes, R. (2020). Identity. In V. Zeigler-Hill & T. K. Shackelford (Eds.), *Springer eBook Collection. Encyclopedia of Personality and Individual Differences* (1st ed., pp. 2136–2145). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-319-24612-3_1132

Harackiewicz, J. M., Smith, J. L., & Priniski, S. J. (2016). Interest matters: The importance of promoting interest in education. *Policy Insights from the Behavioral and Brain Sciences*, *3*(2), 220–227. https://doi.org/10.1177/2372732216655542

Hazari, Z., Dou, R., Sonnert, G., & Sadler, P. M. (2022). Examining the relationship between informal science experiences and physics identity: Unrealized possibilities. *Physical Review Physics Education Research*, *18*(1). https://doi.org/10.1103/PhysRevPhysEducRes.18.010107

Henriksen, E. K., & Frøyland, M. (2000). The contribution of museums to scientific literacy: Views from audience and museum professionals. *Public Understanding of Science*, *9*(4), 393–415. https://doi.org/10.1088/0963-6625/9/4/304

Herman, B. C., Sadler, T. D., Zeidler, D. L., & Newton, M. H. (2017). A socioscientific issues approach to environmental education. In G. Reis & J. Scott (Eds.), *Environmental Discourses in Science Education Ser: v.3. International Perspectives on the Theory and Practice of Environmental Education* (Vol. 3, pp. 145–161). Springer. https://doi.org/10.1007/978-3-319-67732-3_11

Herrmann-Abell, C. F., & DeBoer, G. E. (2017). Investigating a learning progression for energy ideas from upper elementary through high school. *Journal of Research in Science Teaching*, *9*(2-3), 71. https://doi.org/10.1002/tea.21411

Hine, A. and Medvecky, F. (2015). Unfinished science in museums: a push for critical science literacy'. *ICOM*, *14*(2), A04.

Hodson, D. (2003). Time for action: Science education for an alternative future. *International Journal of Science Education*, *25*(6), 645–670. https://doi.org/10.1080/09500690305021

Hodson, D. (2020). Going beyond STS education: Building a curriculum for sociopolitical activism. *Canadian Journal of Science, Mathematics and Technology Education*, *20*(4), 592–622. https://doi.org/10.1007/s42330-020-00114-6

Hohenstein, J., & Moussouri, T. (2018). *Museum learning: Theory and research as tools for enhancing practice*. Routledge. https://www.taylorfrancis.com/books/9781315696447 https://doi.org/10.4324/9781315696447

Howarth, C., Parsons, L., & Thew, H. (2020). Effectively communicating climate science beyond academia: Harnessing the heterogeneity of climate knowledge. *One Earth (Cambridge, Mass.)*, *2*(4), 320–324. https://doi.org/10.1016/j.oneear.2020.04.001

International Council of Museums. (Kyoto 2019). *Resolutions adopted by ICOM'S 34th general assembly: Resolution #1: 'On sustainability and the implementation of Agenda 2030,* *Transforming our World.’*. https://icom.museum/wp-content/uploads/2019/09/Resolutions_2019_EN.pdf

International Renewable Energy Agency. (2021). *World energy transitions outlook: 1.5°C pathway*. International Renewable Energy Agency.

Jensen, B. B., & Schnack, K. (1997). The action competence approach in environmental education. *Environmental Education Research*, *3*(2), 163–178. https://doi.org/10.1080/1350462970030205

Jorgenson, S. N., Stephens, J. C., & White, B. (2019). Environmental education in transition: A critical review of recent research on climate change and energy education. *The Journal of Environmental Education*, *50*(3), 160–171. https://doi.org/10.1080/00958964.2019.1604478

Kahn, S., & Zeidler, D. L. (2017). Using our heads and HARTSS*: Developing perspective-taking skills for socioscientific reasoning (*Humanities, ARTs, and Social Sciences). *Journal of Science Teacher Education*, *27*(3), 261–281. https://doi.org/10.1007/s10972-016-9458-3

Kalmi, P., Trotta, G., & Kažukauskas, A. (2021). Energy-related financial literacy and electricity consumption: Survey-based evidence from Finland. *Journal of Consumer Affairs*, *55*(3), 1062–1089. https://doi.org/10.1111/joca.12395

Kalmi P, Trotta G, Kazukauskas A. (2017). *The role of energy literacy as a component of financial literacy: Survey - based evidence from Finland* (IAEE conference).

Kaplan, A., & Flum, H. (2010). Achievement goal orientations and identity formation styles. *Educational Research Review*, *5*(1), 50–67. https://doi.org/10.1016/j.edurev.2009.06.004

Kapur, M. (2016). Examining productive failure, productive success, unproductive failure, and unproductive success in learning. *Educational Psychologist*, *51*(2), 289–299. https://doi.org/10.1080/00461520.2016.1155457

Kempton, W., & Holland, D. (2003). Identity and sustained environmental practice.: In S. Clayton & S. Opotow (Eds.), Identity and the natural environment (pp. 317-341). Hong Kong, China: MIT Press.

Kilinc, A., Demiral, U., & Kartal, T. (2017). Resistance to dialogic discourse in SSI teaching: The effects of an argumentation-based workshop, teaching practicum, and induction on a preservice science teacher. *Journal of Research in Science Teaching*, *54*(6), 764–789. https://doi.org/10.1002/tea.21385

Kinslow, A. T., Sadler, T. D., & Nguyen, H. T. (2018). Socio-scientific reasoning and environmental literacy in a field-based ecology class. *Environmental Education Research*, *20*(2), 1–23. https://doi.org/10.1080/13504622.2018.1442418

Knipfler, K. (2009). *Pro or con nanotechnology? Support for rritical thinking and reflective judgement at science museums*. Dissertation.

Kollmuss, A., & Agyeman, J. (2002). Mind the gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental Education Research*, *8*(3), 239–260. https://doi.org/10.1080/13504620220145401

Kormos, C., & Gifford, R. (2014). The validity of self-report measures of proenvironmental behavior: A meta-analytic review. *Journal of Environmental Psychology*, *40*, 359–371. https://doi.org/10.1016/j.jenvp.2014.09.003

Koster, E. H. (1999). In Search of relevance: Science centers as innovators in the evolution of museums. *Daedalus*, *28*(2), 277–296.

Krapp, A. (1999). Interest, motivation and learning: An educational-psychological perspective. *European Journal of Psychology of Education*, *XIV* (1), 23–40.

Krapp, A. (2002). Structural and dynamic aspects of interest development: theoretical considerations from an ontogenetic perspective. *Learning and Instruction*, *12*, 383–404.

Kultusministerkonferenz (2005). Bildungsstandards im Fach Physik für den Mittleren Schulabschluss: Beschluss vom 16.12.2004, Ausgabe Beschlüsse der Kultusministerkonferenz. *Sekretariat Der Ständigen Konferenz Der Kultusminister Der Länder in Der Bundesrepublik Deutschland.*

Lackner, B., Leal Filho, W., McGhie, H., & 0013892 (Eds.). (2019). *Climate change management*. *addressing the challenges in communicating climate change across various audiences* (1st ed. 2019). Springer International Publishing; Imprint: Springer.

Laslo, E., Baram-Tsabari, A., & Lewenstein, B. V. (2011). A growth medium for the message: Online science journalism affordances for exploring public discourse of science and ethics. *Journalism*, *12*(7), 847–870. https://doi.org/10.1177/1464884911412709

Lee, E. A., & Brown, M. J. (2018). Connecting inquiry and values in science education. *Science & Education*, *27*(1-2), 63–79. https://doi.org/10.1007/s11191-017-9952-9

Lee, L.-S., Chang, L.-T., Lai, C.-C., Guu, Y.-H., & Lin, K.-Y. (2015). Energy literacy of vocational students in Taiwan. *Environmental Education Research*, *23*(6), 855–873. https://doi.org/10.1080/13504622.2015.1068276

Lee, O., & Grapin, S. E. (2022). The role of phenomena and problems in science and STEM education: Traditional, contemporary, and future approaches. *Journal of Research in Science Teaching*, *59*(7), 1301–1309. https://doi.org/10.1002/tea.21776

Lee, Y.-F., Nguyen, H. B. N., & Sung, H.-T. (2022). Energy literacy of high school students in Vietnam and determinants of their energy-saving behavior. *Environmental Education Research*, *12*(5), 1–18. https://doi.org/10.1080/13504622.2022.2034752

Lewalter, D., Gegenfurtner, A., & Renninger, K. A. (2021). Out-of-school programs and interest: Design considerations based on a meta-analysis. *Educational Research Review*, *34*(1), 100406. https://doi.org/10.1016/j.edurev.2021.100406

Lewalter, D., & Geyer, C. (2009). Motivationale Aspekte von schulischen Besuchen in naturwissenschaftlich-technischen Museen. *Zeitschrift Für Erziehungswissenschaft*, *12*(1), 28–44. https://doi.org/10.1007/s11618-009-0060-8

Liu, X. (2013). Expanding notions of scientific literacy: A reconceptualization of aims of science education in the knowledge society. In N. Mansour & R. Wegerif (Eds.), *Cultural Studies of Science Education: Vol. 8. Science education for diversity: Theory and practice* (Vol. 8, pp. 23–39). Springer. https://doi.org/10.1007/978-94-007-4563-6_2

Liu, X., & Park, M. (2014). Contextual dimensions of the energy concept and implications for energy teaching and learning. In R. F. Chen (Ed.), *Teaching and learning of energy in K-12 education* (pp. 175–186). Springer. https://doi.org/10.1007/978-3-319-05017-1_10

Longnecker, N. (2016). An integrated model of science communication — More than providing evidence. *Journal of Science Communication*, *15*(05), Y01. https://doi.org/10.22323/2.15050401

Lowan-Trudeau, G., & Fowler, T. A. (2021). Towards a theory of critical energy literacy: The youth strike for climate, renewable energy and beyond. *Australian Journal of Environmental Education*, *17*, 1–11. https://doi.org/10.1017/aee.2021.15

Marcia, J. E. (1966). Development and validation of ego-identity status. *Journal of Personality and Social Psychology*, *3*(5), 551–558. https://doi.org/10.1037/h0023281

Martins, A., Madaleno, M., & Dias, M. F. (2020). Energy literacy: What is out there to know? *Energy Reports*, *6*(3), 454–459. https://doi.org/10.1016/j.egyr.2019.09.007

McBride, B. B., Brewer, C. A., Berkowitz, A. R., & Borrie, W. T. (2013). Environmental literacy, ecological literacy, ecoliteracy: What do we mean and how did we get here? *Ecosphere*, *4*(5), 1–20. https://doi.org/10.1890/ES13-00075.1

McCaffrey, Mark, Minda Berbeco, Minda, Scott, Eugenie. (2012, December 7). *Toward a climate & energy literate society: Recommendations from the climate and energy literacy summit*. Berkeley, California. National Center for Science Education.

McGhie, H. (2018). *Museums as key sites to accelerate climate change education, action, research and partnerships: Non-party stakeholder submission to the Talanoa Dialogue from the ‘International Symposium on Climate Change and Museums*`.

McGhie, H. (2020). Evolving climate change policy and museums. *Museum Management and Curatorship*, *35*(6), 653–662. https://doi.org/10.1080/09647775.2020.1844589

McGuire, N. M. (2015). Environmental education and behavioral change: An identity-based environmental education model. *International Journal of Environmental & Science Education*, *10*(5), 695–715.

Michel, H. (2020). *From local to global: The role of knowledge, transfer, and capacity building for successful energy transition*. SP III 2020–603.

Miller, C. A., Iles, A., & Jones, C. F. (2013). The Social dimensions of energy transitions. *Science as Culture*, *22*(2), 135–148. https://doi.org/10.1080/09505431.2013.786989

Moser, S. C. (2016). Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say? *WIREs Climate Change*, *7*(3), 345–369. https://doi.org/10.1002/wcc.403

National Academies of Sciences, Engineering, and Medicine. (2018). How people learn II: Learners, contexts, and cultures. *National Academies Press.* Advance online publication. https://doi.org/10.17226/24783

Navas Iannini, A. M., & Pedretti, E. (2022). Museum staff perspectives about a sustainability exhibition: What do they tell us about scientific literacy? *International Journal of Science Education, Part B*, *12*(1), 1–21. https://doi.org/10.1080/21548455.2021.2015638

Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). Towards a learning progression of energy. *Journal of Research in Science Teaching*, *50*(2), 162–188. https://doi.org/10.1002/tea.21061

Newton, M. H., & Zeidler, D. L. (2020). Developing socioscientific perspective taking. *International Journal of Science Education*, *42*(8), 1302–1319. https://doi.org/10.1080/09500693.2020.1756515

NGSS Lead States. (2013). *Next Generation Science Standards.* Retrieved from www.nextgenscience.org.

Nisa, C. F., Bélanger, J. J., Schumpe, B. M., & Faller, D. G. (2019). Meta-analysis of randomised controlled trials testing behavioural interventions to promote household action on climate change. *Nature Communications*, *10*(1), 4545. https://doi.org/10.1038/s41467-019-12457-2

Nordine, J. (Ed.). (2016). *Teaching energy across the sciences, K-12*. NSTApress National Science Teachers Association.

OECD. (2019). *OECD future of education and skills 2030: OECD learning compass 2030: retreived from: https://www.oecd.org/education/2030-project/teaching-and-learning/learning/*.

Osborne, J. (2007). Science education for the twenty first century. *EURASIA Journal of Mathematics, Science and Technology Education*, *3*(3). https://doi.org/10.12973/ejmste/75396

Pahnke, J., O’Donnell, C., & Bascopé, M. (2019). *Using science to do social good: STEM education for sustainable development.* Position Paper developed in preparation for the second “International Dialogue on STEM Education” (IDoS) in Berlin, December 5-6, 2019

Pedretti, E. (2002). T. Kuhn Meets T. Rex: Critical conversations and new directions in science centers and science museums. *Studies in Science Education*, *37*(1), 1–41. https://doi.org/10.1080/03057260208560176

Pedretti, E., & Navas Iannini, A. M. (2020a). *Controversy in science museums: Re-imagining spaces and practice*. Routledge.

Pedretti, E., & Iannini, A. M. N. (2020b). Towards fourth-generation science museums: Changing goals, changing roles: *Canadian Journal of Science, Mathematics and Technology Education*, *20*(4), 700–714. https://doi.org/10.1007/s42330-020-00128-0

Pedretti, E. G. (2004). Perspectives on learning through research on critical issues-based science center exhibitions. *Science Education*, *88*(S1), S34-S47. https://doi.org/10.1002/sce.20019

Phelan, S., Specht, I., Schnotz, W., & Lewalter D. (2017). Attitude change when presenting science museum visitors with risk-benefit information. *Science Education*, 1–14. https://doi.org/10.1002/sce.21296

Presley, M. L., Sickel, A. J., Muslu, N., Merle-Johnson, D., Witzig, S. B., Izci, K., & Sadler, T. s (2013). A Framework for socio-scientifc issues based education. *Science Educator*, *22*(1), 26–32.

Rahmani, L., Haasova, S., Czellar, S., Clergue, V., & Martin, C. (2022). How often do you think about your relationship with nature? The measurement of environmental identity salience and its relationship with proenvironmental behaviors. *Frontiers in Psychology*, *13*, 877978. https://doi.org/10.3389/fpsyg.2022.877978

Rau, H., Nicolai, S., & Stoll-Kleemann, S. (2022). A systematic review to assess the evidence-based effectiveness, content, and success factors of behavior change interventions for enhancing pro-environmental behavior in individuals. *Frontiers in Psychology*, *13*, 901927. https://doi.org/10.3389/fpsyg.2022.901927

Reimers Arias, F., & Chung, C. K. (Eds.). (2016). *Teaching and learning for the twenty-first century: Educational goals, policies, and curricula from six nations*. Harvard Education Press.

Rennie, L. J., & Williams, G. F. (2006). Adults’ learning about science in free-choice settings. *International Journal of Science Education*, *28*(8), 871–893. https://doi.org/10.1080/09500690500435387

Renninger, K. A., & Bachrach, J. E. (2015). Studying triggers for interest and engagement using observational methods. *Educational Psychologist*, *50*(1), 58–69. https://doi.org/10.1080/00461520.2014.999920

Renninger, K. A. & Hidi, S. (2016). *The power of interest for motivation and engagement*. Routledge. https://doi.org/10.4324/9781315771045

Rieckmann, M. (2017). *Education for sustainable development goals: Learning objectives*. UNESCO, Paris.

Roberts, D. A. (2007). Scientific literacy / science literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 729–780). Erlbaum.

Roberts, D. A., & Bybee, R. W. (2014). Scientific literacy, science literacy, and science education. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of Research on Science Education* (pp. 545–558). Routledge. https://doi.org/10.4324/9780203097267.ch27

Romine, W. L., Sadler, T. D., & Kinslow, A. T. (2017). Assessment of scientific literacy: Development and validation of the quantitative assessment of socio-scientific reasoning (QuASSR). *Journal of Research in Science Teaching*, *54*(2), 274–295. https://doi.org/10.1002/tea.21368

Rounds, J. (2006). Doing identity work in museums. *Curator the Museum Journal*, *49*, 133–150.

Sadler, T. D. (2004). Informal reasoning regarding socioscientific issues: A critical review of research. *Journal of Research in Science Teaching*, *41*(5), 513–536. https://doi.org/10.1002/tea.20009

Sadler, T. D. (2009). Socioscientific issues in science education: labels, reasoning, and transfer. *Cultural Studies of Science Education*, *4*(3), 697–703. https://doi.org/10.1007/s11422-008-9133-x

Sadler, T. D. (Ed.). (2011). *Socio-scientific issues in the classroom* (Vol. 39). Springer Netherlands. https://doi.org/10.1007/978-94-007-1159-4

Sadler, T. D., Barab, S. A., & Scott, B. (2007). What do students gain by engaging in socioscientific inquiry? *Research in Science Education*, *37*(4), 371–391. https://doi.org/10.1007/s11165-006-9030-9

Sadler, T. D., Foulk, J. A., & Friedrichsen, P. J. (2016). Evolution of a model for socio-scientific issue teaching and learning. *International Journal of Education in Mathematics, Science and Technology*, *5*(1), 75. https://doi.org/10.18404/ijemst.55999

Sanz-Hernández, A. (2020). How to change the sources of meaning of resistance identities in historically coal-reliant mining communities. *Energy Policy*, *139*, 111353. https://doi.org/10.1016/j.enpol.2020.111353

Schleicher, A. (2018). *World class: How to build a 21st-century school system*. *Strong performers and successful reformers in education*. OECD.

Schwan, S., Grajal, A., & Lewalter, D. (2014). Understanding and engagement in places of science experience: Science museums, science centers, zoos, and aquariums. *Educational Psychologist*, *49*(2), 70–85. https://doi.org/10.1080/00461520.2014.917588

Science Centre World Summit. (15-17 November, 2017). *Tokyo Protocol: On the role of science centres and science museums worldwide in support of the United Nations sustainable development goals.* Tokyo.

Sjöström, J., & Eilks, I. (2018). Reconsidering different visions of scientific literacy and science education based on the concept of Bildung, *24*, 65–88. https://doi.org/10.1007/978-3-319-66659-4_4

Smith, C., & Watson, J. (2018). STEM: Silver bullet for a viable future or just more flatland? *Journal of Futures Studies*, *22*(4), 25–44.

Stapleton, S. R. (2015). Environmental identity development through social interactions, action, and recognition. *The Journal of Environmental Education*, *46*(2), 94–113. https://doi.org/10.1080/00958964.2014.1000813

Steg, L. (2016). Values, norms, and intrinsic motivation to act proenvironmentally. *Annual Review of Environment and Resources*, *41*(1), 277–292. https://doi.org/10.1146/annurev-environ-110615-085947

Steg, L. (2023). Psychology of climate change. *Annual Review of Psychology*, *74*, 391–421. https://doi.org/10.1146/annurev-psych-032720-042905

Steg, L., Perlaviciute, G., Sovacool, B. K., Bonaiuto, M., Diekmann, A., Filippini, M., Hindriks, F., Bergstad, C. J., Matthies, E., Matti, S., Mulder, M., Nilsson, A., Pahl, S., Roggenkamp, M., Schuitema, G., Stern, P. C., Tavoni, M., Thøgersen, J., & Woerdman, E. (2021). A research agenda to better understand the human dimensions of energy transitions. *Frontiers in Psychology*, *12*, 672776. https://doi.org/10.3389/fpsyg.2021.672776

Steg, L., Perlaviciute, G., & van der Werff, E. (2016). Understanding the human dimensions of a sustainable energy transition. In T. Brosch, D. Sander, & M. K. Patel (Eds.), *Understanding the Human Factor of the Energy Transition: Mechanisms Underlying Energy-Relevant Decisions and Behaviors* (Vol. 6, pp. 9–25). Frontiers Media SA. https://doi.org/10.3389/fpsyg.2015.00805

Stets, J. E., & Biga, C. F. (2003). Bringing identity theory into environmental sociology. *Sociological Theory*, *21*(4), 398–423. https://doi.org/10.1046/j.1467-9558.2003.00196.x

Stocklmayer, S. M., Rennie, L. J., & Gilbert, J. K. (2010). The roles of the formal and informal sectors in the provision of effective science education. *Studies in Science Education*, *46*(1), 1–44. https://doi.org/10.1080/03057260903562284

Sutton, S. (2020). The evolving responsibility of museum work in the time of climate change. *Museum Management and Curatorship*, *35*(6), 618–635. https://doi.org/10.1080/09647775.2020.1837000

Sutton, S., & Robinson, C. (2020). Museums and public climate action. *Journal of Museum Education*, *45*(1), 1–4. https://doi.org/10.1080/10598650.2020.1722513

Sutton, S., E. Wylie, B. Economopolous, C. O’Brien, S. Shapiro, and S. Xu (2017). Museums and the future of a healthy world: “Just, verdant and peaceful”. *Curator: The Museum Journal*, *60*(2), 429–441.

The Extraordinary General Assembly of ICOM (2022, August 24). Standing Committee for the Museum Definition – ICOM Define Final Report. Prague. ICOM, International Council of Museums.

Toplak, M. E., & Stanovich, K. E. (2003). Associations between myside bias on an informal reasoning task and amount of post-secondary education. *Applied Cognitive Psychology*, *17*(7), 851–860. https://doi.org/10.1002/acp.915

U.S. Department of Energy (2017). *Energy literacy: Essential principles and fundamental concepts for energy education. A framework for energy education for learners of all ages*. Washington, DC: U.S. Department of Energy.

United Nations. (2015). *Transforming our world: the 2030 Agenda for: A/RES/70/1*. Resolution adopted by the General Assembly on 25 September 2015.

United Nations. (2021). *The sustainable development goals report 2021.*

United Nations Environment Programme. (2019). *Emission gap report 2019*. Nairobi. UNEP.

Valladares, L. (2021). Scientific literacy and social transformation: Critical perspectives about science participation and emancipation. *Science & Education*, *30*(3), 557–587. https://doi.org/10.1007/s11191-021-00205-2

van de Wetering, J., Leijten, P., Spitzer, J., & Thomaes, S. (2022). Does environmental education benefit environmental outcomes in children and adolescents? A meta-analysis. *Journal of Environmental Psychology*, *81.* https://doi.org/10.1016/j.jenvp.2022.101782

Verhoeven, M., Poorthuis, A. M. G., & Volman, M. (2019). The role of school in adolescents' identity development. A literature review. *Educational Psychology Review*, *31*(1), 35–63. https://doi.org/10.1007/s10648-018-9457-3

Wang, J. C., & Wang, T. H. (2023). Learning effectiveness of energy education in junior high schools: Implementation of action research and the predict-observe-explain model to STEM course. *Heliyon*, *9*(3), e14058. https://doi.org/10.1016/j.heliyon.2023.e14058

World Economic Forum. (2021, January 19). *The Global Risks Report 2021.*

Zeidler, D. L., Herman, B. C., & Sadler, T. D. (2019). New directions in socioscientific issues research. *Disciplinary and Interdisciplinary Science Education Research*, *1*(1), 1:11. https://doi.org/10.1186/s43031-019-0008-7

Zeidler, D. L., & Newton, M. H. (2017). Using a socioscientific issues framework for climate change education: An ecojustice approach, 56–65. https://doi.org/10.4324/9781315629841-5

Zeidler, D. L., Sadler, T. D., Simmons, M. L., & Howes, E. V. (2005). Beyond STS: A research-based framework for socioscientific issues education. *Science Education*, *89*(3), 357–377. https://doi.org/10.1002/sce.20048